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8.5.4 Transport infrastructure

Climate proofing and adaptation will require substantial infrastructure investments (see Section 8.4 and the Working Group II (WGII) Contribution to the IPCC Fifth Assessment Report (AR5), Chapter 15). This will generate additional freight transport if implemented outside of the normal infrastructure maintenance and upgrade cycle. Climate proofing of transport infrastructure can take many forms (ADB, 2011a; Highways Agency, 2011) varying in the amount of additional freight movement required. Resurfacing a road with more durable materials to withstand greater temperature extremes may require no additional freight movement, whereas re-routing a road or rail link, or installing flood protection, are likely to generate additional logistics demands, which have yet to be quantified.

Adaptation efforts are likely to increase transport infrastructure costs (Hamin & Gurran, 2009), and influence the selection of projects for investment. In addition to inflating maintenance costs (Jollands et al., 2007; Larsen et al., 2008), climate proofing would divert resources that could otherwise be invested in extending networks and expanding capacity. This is likely to affect all transport modes to varying degrees. If, for example, climate proofing were to constrain the development of a rail network more than road infrastructure, it might inhibit a modal shift to less carbon-intensive rail services.

The future choice of freight and passenger traffic between modes may also become more responsive to their relative sensitivity to extreme weather events (Koetse and Rietveld, 2009; Taylor and Philp, 2010). The exposure of modes to climate risks include aviation (Eurocontrol, 2008), shipping (Becker et al., 2012), and land transport (Hunt and Watkiss, 2011). Little attempt has been made to conduct a comparative analysis of their climate risk profiles, to assess the effects on the modal choice behaviour of individual travellers and businesses, or to take account of regional differences in the relative vulnerability of different transport modes to climate change (Koetse and Rietveld, 2009).

Overall, the transport sector will be highly exposed to climate change and will require extensive adaptation of infrastructure, operations, and service provision. It will also be indirectly affected by the adaptation and decarbonization of the other sectors that it serves. Within the transport sector there will be a complex interaction between adaptation and mitigation efforts. Some forms of adaptation, such as infrastructural climate proofing, will be likely to generate more freight and personal movement, while others, such as the NSR, could substantially cut transport distances and related emissions.

8.6 Costs and potentials

For transport, the potential for reducing GHG emissions, as well as the associated costs, varies widely across countries and regions. Appropriate policies and measures that can accomplish such reductions also vary (see Section 8.10) (Kahn Ribeiro et al., 2007; Li, 2011). Mitigation costs and potentials are a function of the stringency of climate goals and their respective GHG concentration stabilization levels (Fischedick et al., 2011; Rogelj et al., 2013). This section presents estimates of mitigation potentials and associated costs from the application of new vehicle and fuel technologies, performance efficiency gains, operational measures, logistical improvements, electrification of modes, and low-carbon fuels and activity reduction for different transport modes (aviation, rail, road, waterborne and cross-modal). Potential CO_2eq emissions reductions from passenger-km (p-km) and tonne-km (t-km) vary widely by region, technology, and mode according to how rapidly the measures and applications can be developed, manufactured, and sold to buyers replacing existing ones in vehicles an fuels or adding to the total fleet, and on the way they are used given travel behaviour choices (Kok et al., 2011). In general, there is a larger emission reduction potential in the transport sector, and at a lower cost, compared to the findings in AR4 (Kahn Ribeiro et al., 2007).

The efforts undertaken to reduce activity, to influence structure and modal shift, to lower energy intensity, and to increase the use of low-carbon fuels, will influence future costs and potentials. Ranges of mitigation potentials have an upper boundary based on what is currently understood to be technically achievable, but will most likely require strong policies to be achieved in the next few decades (see Section 8.10). Overall reductions are sensitive to per-unit transport costs (that could drop with improved vehicle efficiency); resulting rebound effects; and shifts in the type, level, and modal mix of activity. For instance, the deployment of more efficient, narrow-body jet aircraft could increase the number of commercially-attractive, direct city-to-city connections, which may result in an overall increase in fleet fuel use compared to hub-based operations.

This assessment follows a bottom-up approach to maintain consistency in assumptions. Table 8.3 outlines indicative direct mitigation costs using reference conditions as baselines, and illustrative examples of existing vehicles and situations for road, aviation, waterborne, and rail (as well as for some cross-mode options) available in the literature. The data presented on the cost-effectiveness of different carbon reduction measures is less detailed than data on the potential CO_2eq savings due to literature gaps. The number of studies assessing potential future GHG reductions from energy intensity gains and use of low-carbon fuels is larger than those assessing mitigation potentials and cost from transport activity, structural change and modal shift, since they are highly variable by location and background conditions.

Key assumptions made in this analysis were:

- cost estimates are based on societal costs and benefits of technologies, fuels, and other measures, and take into account initial costs as well as operating costs and fuel savings;
- existing transport options are compared to current base vehicles and activities, whereas future options are compared to estimates of baseline future technologies and other conditions;

- fuel price projections are based on the IEA World Energy Outlook (IEA, 2012b) and exclude taxes and subsidies where possible;
- discount rates of 5 % are used to bring future estimates back to present (2013) values, though the literature considered has examined these issues mostly in the developed-world context; and
- indirect responses that occur through complex relationships within sectors in the larger socioeconomic system are not included (Stepp et al., 2009).

Results in Table 8.3 indicate that, for LDVs, efficiency improvement potentials of 50 % in 2030 are technically possible compared to 2010, with some estimates in the literature even higher (NRC, 2010). Virtually all of these improvements appear to be available at very low, or even negative, societal costs. Electric vehicles have a CO_2eq reduction cost highly correlated with the carbon intensity of electricity generation: using relatively high-carbon intensity electricity systems (500–600 gCO_2eq/kWh), EVs save little CO_2eq compared to conventional LDVs and the mitigation cost can be many hundreds of dollars per tonne; for very low-carbon electricity (below 200 gCO_2eq/kWh) the mitigation cost drops below 200 USD_{2010}/tCO_2eq. In the future, with lower battery costs and low-carbon electricity, EVs could drop below 100 USD_{2010}/tCO_2eq and even approach zero net cost.

For long-haul HDVs, up to a 50 % reduction in energy intensity by 2030 appears possible at negative societal cost per tCO_2eq due to the very large volumes of fuel they use. HDVs used in urban areas where their duty cycle does not require as much annual travel (and fuel use), have a wider range of potentials and costs, reaching above 100 USD_{2010}/t CO_2eq. Similarly, inter-city buses use more fuel annually than urban buses, and as a result appear to have more low-cost opportunities for CO_2eq reduction (IEA, 2009; NRC, 2010; TIAX, 2011).

Recent designs of narrow and wide-body commercial aircraft are significantly more efficient than the models they replace, and provide CO_2eq reductions at net negative societal cost when accounting for fuel savings over 10–15 years of operation at 5 % discount rate. An additional 30–40 % CO_2eq reduction potential is expected from future new aircraft in the 2020–2030 time frame, but the mitigation costs are uncertain and some promising technologies, such as open rotor engines, appear expensive (IEA, 2009; TOSCA, 2011).

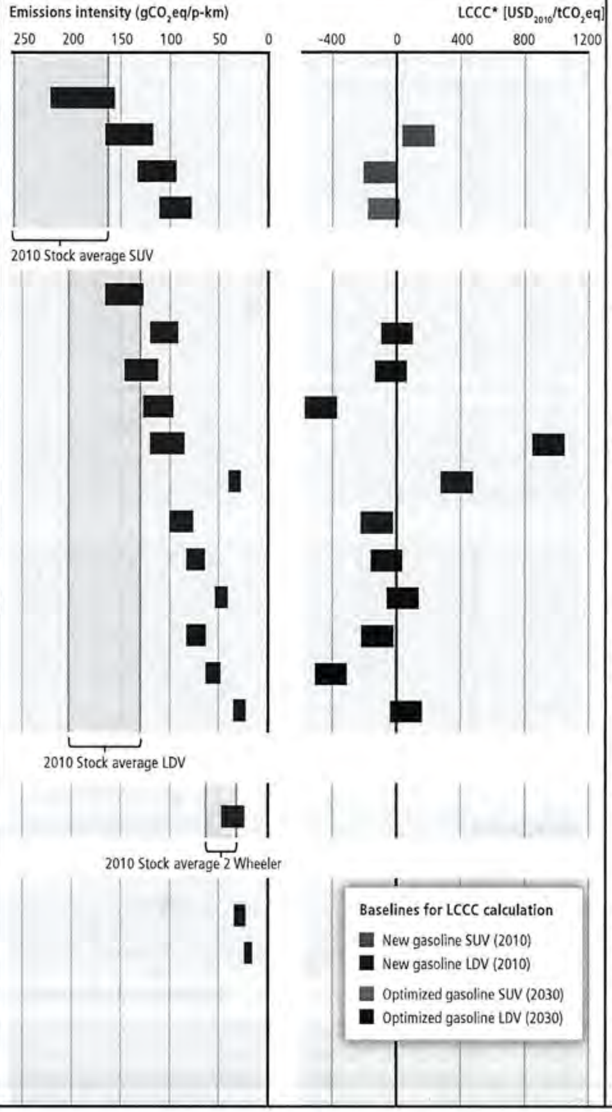
For virtually all types of ocean-going ships including container vessels, bulk carriers, and oil tankers, the potential reduction in CO_2eq emissions is estimated to be over 50 % taking into account a wide range of technology and operational changes. Due to the large volume of fuel used annually by these ships, the net cost of this reduction is likely to be negative (Buhaug and et. al, 2009; Crist, 2009).

Key factors in the long term decarbonization of rail transport will be the electrification of services and the switch to low-carbon electricity generation, both of which will vary widely by country. Potential improvements of 35 % energy efficiency for United States rail freight, 46 % for European Union rail freight and 56 % for EU passenger rail services have been forecast for 2050 (Anderson et al., 2011; Vyas et al., 2013). The EU improvements will yield a 10–12 % reduction in operating costs, though no information is available on the required capital investment in infrastructure and equipment.

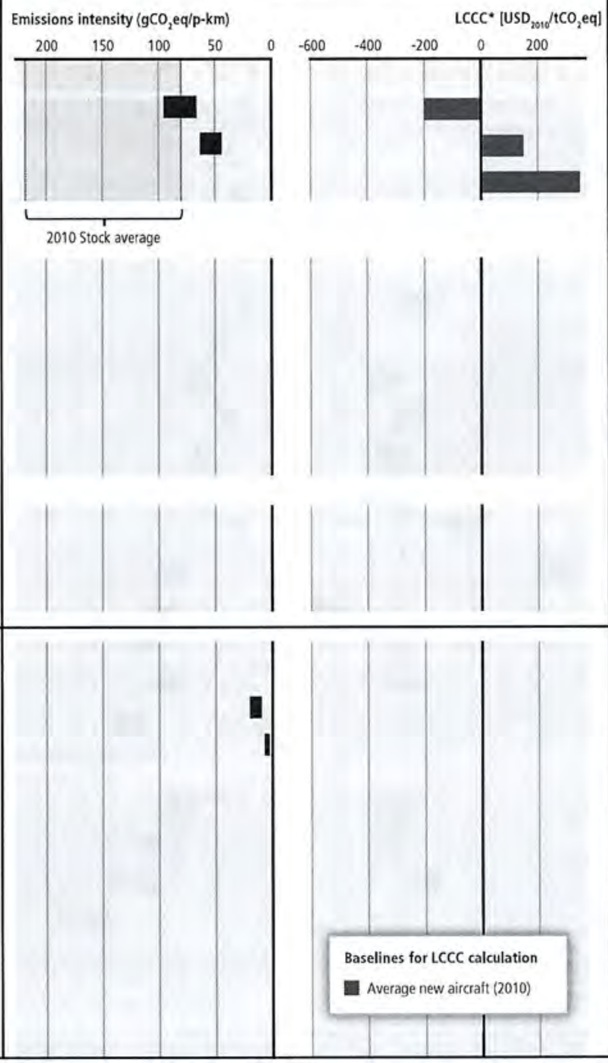
Regarding fuel substitution in all modes, some biofuels have the potential for large CO_2eq reduction, although net GHG impact assessments are complex (see Sections 8.3 and 11.13). The cost per tonne of CO_2eq avoided will be highly dependent on the net CO_2eq reduction and the relative cost of the biofuel compared to the base fuel (e. g., gasoline or diesel), and any technology changes required to the vehicles and fuel distribution network in order to accommodate new fuels and blends. The mitigation cost is so sensitive that, for example, while an energy unit of biofuel that cuts CO_2eq emissions by 80 % compared to gasoline and costs 20 % more has a mitigation cost of about 80 USD/t CO_2eq, if the biofuel's cost drops to parity with gasoline, the mitigation cost drops to 0 USD/t CO_2eq (IEA, 2009).

The mitigation potentials from reductions in transport activity consider, for example, that "walking and cycle track networks can provide 20 % (5–40 % in sensitivity analyses) *induced* walking and cycle journeys that would not have taken place without the new networks, and around 15 % (0–35 % in sensitivity analyses) of current journeys less than 5 km made by car or public transport can be *replaced* by walking or cycling" (Sælensminde, 2004). Urban journeys by car longer than 5 km can be replaced by combined use of non-motorized and intermodal public transport services (Tirachini and Hensher, 2012).

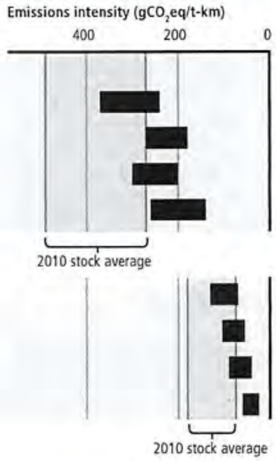
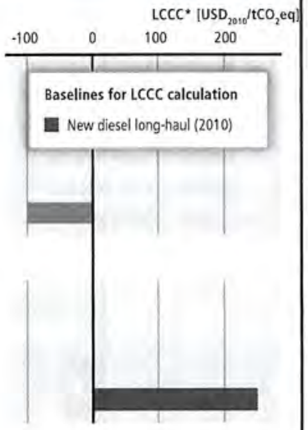
Table 8.3 | Selected CO_2eq mitigation potentials and costs for various modes in the transport sector with baselines of stock average fleet compared with 2010 new vehicles and 2030 projected vehicle based on available data. (See footnotes at end of Table).

Mitigation options in passenger transport	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Road				
New sport utility vehicles (SUV), mid-size			**Baseline 2010 stock average vehicles** Industry average; 164 gCO_2/p-km (6). Drive-train redesigns may yield 25% improvement. Additional reductions from light-weighting, aerodynamics, more efficient accessories (6). Most current and many future LDV efficiency improvements are at negative cost of USD/tCO_2 (4, 47). Potential 40–60% fuel efficiency gains by 2030 compared to similar size 2010 LDVs (5). **2030 conventional/hybrid:** - mid-size; 70–120 gCO_2/p-km (25). **2010 EV:** - 80–125 gCO_2/p-km using high-carbon electricity grid at 600 gCO_2/kWh; - 28–40 gCO_2/p-km using low-carbon grid electricity at 200 gCO_2/kWh. Likely over 200 USD/tCO_2 in 2010 even with low-carbon grid electricity. **2030 EV:** - 55–235 USD/tCO_2 with high-carbon electricity. - 0–100 USD/tCO_2 with low-carbon electricity (5). EV efficiency 0.2–0.25 kWh/km on road (7). Battery cost: - 750 USD/kWh in 2010; - 200–300 USD /kWh in 2030 (11). Vehicle intensity (well-to-wheel) of 144–180 gCO_2/100km at 0.20–0.25 kWh/km. **PHEV:** 15–70% well-to-wheel more efficient than baseline ICEV (7); 28–50% more efficient by 2030 (5).	Average CO_2 emissions level of new cars in the EU decreased from 170 gCO_2/km in 2001 to 136 gCO_2/km in 2011 (43, 47) **New mid-size gasoline:** 2012 Toyota Yaris hybrid; 79 gCO_2/p-km (6). **New mid-size Diesel:** Volkswagen Golf Blue motion 1.6 TDI: 99 gCO_2/p-km (6) **EVs:** 2013 Nissan Leaf: 24 kWh has 175 km range on New European Driving Cycle, ranging from 76 to 222 km depending on driving conditions (6).
2010 Gasoline				
2010 Hybrid gasoline				
2030 Gasoline				
2030 Hybrid gasoline				
New light duty vehicles (LDV), mid-size				
2010 Gasoline				
2010 Hybrid gasoline				
2010 Diesel				
2010 Compressed natural gas				
2010 Electric, 600 g CO_2eq/kWh_e				
2010 Electric, 200 g CO_2eq/kWh_e				
2030 Gasoline				
2030 Hybrid gasoline				
2030 Hybrid gasoline/biofuel* (50/50 share)				
2030 Diesel				
2030 Compressed natural gas				
2030 Electric, 200 gCO_2eq/kWh_e				
New 2 wheeler (Scooter up to 200 cm³ cylinder capacity)			**Baseline: 2010 stock average scooters** Up to 200 cc typical for Asia (48).	
2010 Gasoline				
New buses, large size			**Baseline: 2010 stock average medium haul bus** 40-passenger occupancy vehicle. Potential efficiency improvement 0–30%.	30% savings in fuel consumption for hybrid buses in Montreal (14).
2010 Diesel				
2010 Hybrid diesel				
Bus rapid transit (BRT)			**BRT** infrastructure cost: 1–27 million USD/km (13). Benefit-cost-ratios of selected BRT systems: Hamilton, Canada 0.37–1.34; Canberra, Australia 1.98–4.78 (12, 36)	**BRT** system, Bogota, Colombia has emission reductions of 250,000 tCO_2eq/yr (12).

*Levelized cost of conserved carbon (LCCC), here at 5% weighted average cost of capital (WACC)

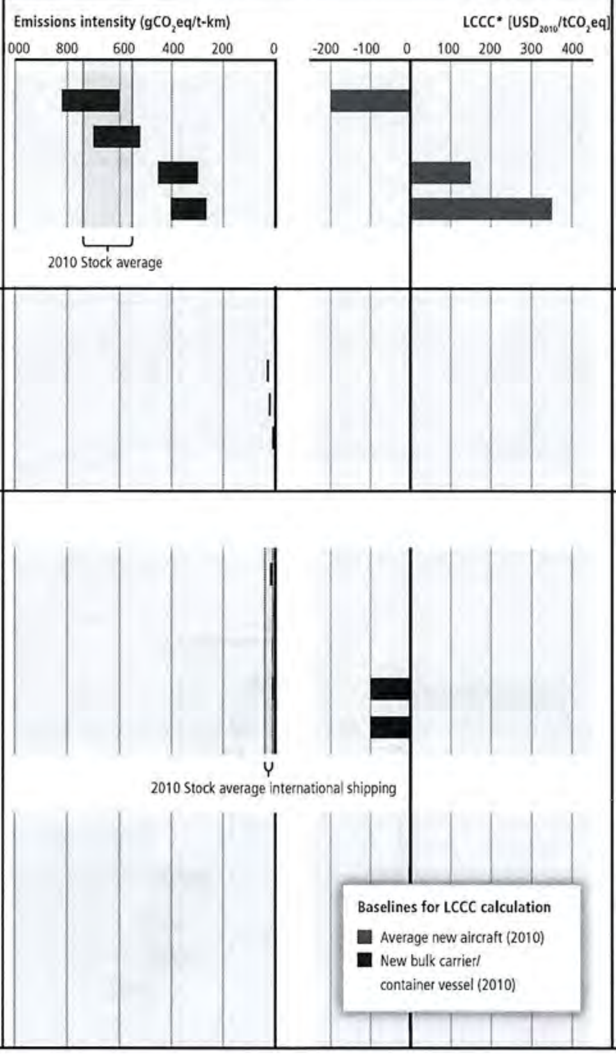
Mitigation options in passenger transport	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Aviation (Commercial, medium to long haul) 2010 Narrow and wide body 2030 Narrow body 2030 Narrow body, open rotor engine			**Baseline: 2010 stock average commercial** (25) Medium haul aircraft; 150-passenger occupancy; average trip distance. **Aircraft efficiency:** Incremental changes to engines and materials up to 20% efficiency improvement. Most efficient present aircraft designs provide 15–30% CO_2 emissions reductions per revenue p-km compared to previous generation aircraft, at net negative costs since fuel savings typically greater than cost of improved technology. (5) **2030 next generation aircraft design:** Advanced engines up to 33% improvement; radical new designs such as 'flying wing', up to 50% improvement. Medium and long-haul (narrow and wide-body) aircraft compared to today's best aircraft design: - 20–35% CO_2 emissions reduction potential by 2025 for conventional aircraft - up to 50% with advanced designs (e.g., flying wing)(2) **Costs:** ~20% CO_2 reduction at <0–100 USD/tCO_2 (narrow body); ~33% reduction at <0–400 USD/tCO_2 (open rotor engine) (34).	New current long-haul wide body: Boeing 787 is 30% more fuel efficient than Boeing 767; Boeing 747-800 is 20% more efficient than Boeing 747-400 (1, 51). New 2010 medium-long-haul, narrow body: Airbus A320 and Boeing 737 (42).
Operational measures			**Taxiing and flight operations** including direct routing, optimum altitude and speed; circling, landing patterns. Improved ground equipment and auxiliary power units can yield 6–12% fuel efficiency gains (3).	
Rail (light rail car) 2010 Electric, 600 g CO_2eq/kWh 2010 Electric, 200 g CO_2eq/kWh			**Baseline: 2010 electric medium haul train** - Based on electricity grid 600 gCO_2/kWh: 3–20 gCO_2/p-km (25). **2010 light rail**; 60 passenger occupancy car: - CO_2 reduction at 4–22 gCO_2/p-km; - Infrastructure cost 14–40 million USD/km (5). **2010 metro:** - CO_2 reduction 3–21 gCO_2/p-km; - Infrastructure cost 27–330 million USD/km (5). **2010 long-distance rail:** - 45–50% reduction in CO_2/p-km (augmented if switch to low-carbon electricity). - 14% reduction in operating costs (allowing for increase in speed and with energy costs excluded from cost calculation (38). - 8–40% efficiency gains (12–19 gCO_2/p-km). - Infrastructure cost 4–75 million USD/km (5). Potential GHG savings from eco-driving 15%; regenerative braking 13%; mass reduction 6% (38).	European rail operations: Passenger: 46% reduction in GHG/p-km by 2050 with 11% reduction in operating costs (43). 8% improvement via regenerative braking systems (Amtrak, US); 40% through design and engine improvements (Shinkansen, Japan) (18). 35% reduction in energy intensity - for US rail operations (17).

*Levelized cost of conserved carbon (LCCC), here at 5% weighted average cost of capital (WACC)

Mitigation options in freight transport	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Road **New medium duty trucks** 2010 Diesel 2010 Diesel hybrid 2010 Compressed natural gas 2030 Diesel **New heavy duty, long-haul trucks** 2010 Diesel 2010 Compressed natural gas 2030 Diesel 2030 Diesel/biofuel (50/50 share)**			**Baseline stock average medium haul HDV** Diesel fuelled HDVs: 76–178 gCO_2/t-km (25). 55% improvement in energy efficiency of tractor trailer HDV between 2010 and 2030 and 50% for other categories of HDV (9, 10). 30–62% improvement by 2030 compared to a similar size 2007–2010 HDV, including increasing load factor by up to 32% (5, 11). Urban HDVs 30–50% reductions at 0–200 USD/tCO_2. Long-haul HDV up to 50% potential CO_2 reduction at negative costs per tCO_2 saved.	New diesel example (47) New diesel hybrid example (47) 'Green Trucks Project' Guangzhou, China, could save 8.6 billion l/yr of fuel and reduce CO_2 emissions by 22.3 $MtCO_2$/yr if all HDVs in the province participated (12). UK 'Logistics Carbon Reduction Scheme' comprising 78 businesses set target for reducing the target intensity of road freight transport by 8% between 2010 and 2015, which is likely to be achieved by the end of 2013.

*Levelized cost of conserved carbon (LCCC), here at 5% weighted average cost of capital (WACC)

**Assuming 70% Less CO_2eq/MJ Biofuel than /MJ Dies



Mitigation options in freight transport	Indicative 2010 stock average baseline CO$_2$eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Aviation (Commercial, medium to long haul) 2010 Dedicated airfreighter 2010 Belly-hold 2030 Improved aircraft 2030 Improved, open rotor engine			See Passenger "Aviation" assumptions above Freight factors for wide-bodied passenger aircraft are around 15-30% whilst narrow bodied planes are typically 0-10% (52),	See Passenger "Aviation" examples above
Rail (freight train) 2010 Diesel, light goods 2010 Diesel, heavy goods 2010 Electric , 200 gCO$_2$eq/kWh			**Baseline** based on electricity grid 600 gCO$_2$/kWh: 6–33 gCO$_2$/t-km (25). - 40–45% reduction in CO$_2$/t-km (augmented if switch to low-carbon electricity). - 14% reduction in operating costs (allowing for increase in speed and with energy costs excluded from cost calculation) (38). Also see passenger "Rail (Light Rail Car)" above.	See passenger "Rail (Light Rail Car)" above
Waterborne 2010 New large international container vessel 2010 Large bulk carrier/tanker 2010 LNG bulk carrier 2030 Optimized container vessel 2030 Optimized bulk carrier			**Baseline: Stock average international ships** 10–40 gCO$_2$/t-km (25). **2010 water craft:** 5–30% CO$_2$/t-km reduction potential; retrofit and maintenance measures 2–20%; total reduction 43% (2020) to 63% (2050) (19). Potential up to 60% CO$_2$ reduction by 2030 from optimized technology and operation (19). 30% or more reduction in CO$_2$/t-km by 2030 at zero cost (30). **2030 water craft:** Business-as-usual reduction in carbon intensity of shipping of 20% between 2010 and 2030 but could rise to 37% with industry initiatives (39).	2010 new medium vessel:(46) Industry initiatives through the Energy Efficiency Design Index and Ship Energy Efficiency Management Programme of the International Maritime Organisation (IMO)(22)
Water craft operations and logistics Slow steaming of container vessel. Inland waterways			**Operations:** Potential CO$_2$ reductions 15–39%; Slow steaming at 3–9kts slower than 24kt baseline. **Cost savings** around 200 USD/tCO$_2$ at bunker fuel price of 700 USD/t and combining savings for carriers and shippers (37). CO$_2$ emissions reductions of 43% per t-km by 2020 (20); - 63% CO$_2$/t-km by 2050 (21); - 25–75% GHG intensity by 2050 (22); - 39–57 % CO$_2$/t-km 'attainable' by 2050; - 59–72 % CO$_2$/t-km is 'optimistic' by 2050 (23)	Global average speed reduction of 15% would give benefits that outweigh costs by 178–617 billion USD by 2050 (31). 'Slow steaming' at 10% slower speed gives 15–19% CO$_2$ emissions reduction; 20% slower speed gives 36–39% (24, 31, 37). Inland waterways potential (46)

*Levelized cost of conserved carbon (LCCC), here at 5% weighted average cost of capital (WACC)

Cross-modal mitigation options	Indicative 2010 stock average baseline CO_2eq emissions and reduction potential	Indicative direct mitigation cost in relation to the baseline (can be positive or negative)	Reference conditions and assumptions made	Illustrative examples
Biofuels	Broad range	Broad range	0–100% excluding land use change effects (26, 33). GHG reduction potential by fuel type: - sugarcane ethanol: 0–80% - enzymatic hydrolysis ethanol: 0–100% - advanced biomass-to-liquid processes (direct gasoline/diesel replacements): 0–100% (33). 80 USD/tCO_2 for biofuels with 80% lower net GHG emissions and 20% higher cost per litre gasoline equivalent (lge) than base fuel (e.g., gasoline).	Brazilian sugarcane: 80% GHG emissions reduction compared with gasoline (excluding land use change effects) (33).
Logistics and freight operations			13–330 USD/tCO_2 (26, 28). ~18% reduction in CO_2/t-km possible from: - speed reduction (7 percentage points) - optimized networks (5 percentage points) - modal switch (4 percentage points) - increased home delivery (1 percentage point) - reduced congestion (1 percentage point) (27).	UK Government best practice programme for freight/logistics at –12 USD/tCO_2 (28). Low-carbon technologies for urban and long-haul road freight –67–110 USD/tCO_2; Route management : ~330 USD/tCO_2.
Eco-driving and driver education			Negative costs per tCO_2 saved even with on-board eco-drive assistance technologies and meters (32). 5–10% reduced fuel consumption (50) 5–25% reduced fuel consumption (15, 16).	Japan: 12% fuel consumption savings through eco-driving-schemes in freight (12).
Activity reduction in urban areas			GHG reduction of up to 30% (29, 40, 41)	Urban densification in the USA over about 50 years could reduce fuel use by 9–16% (35).

Selected CO_2eq mitigation potentials resulting from changes in transport modes with different emission intensities (tCO_2eq/p-km or /t-km) and associated levelized cost of conserved carbon (LCCC in USD_{2010}/tCO_2eq saved). Estimates are indicative. Variations in emission intensities stem from variation in vehicle efficiencies and occupancy/load rates. Estimated LCCC for passenger road transport options are point estimates ±100 USD_{2010}/tCO_2eq based on central estimates of input parameters that are very sensitive to assumptions (e.g., specific improvement in vehicle fuel economy to 2030, specific biofuel CO_2eq intensity, vehicle costs, fuel prices). They are derived relative to different baselines (see legend for colour coding) and need to be interpreted accordingly. Estimates for 2030 are based on projections from recent studies, but remain inherently uncertain. LCCC for aviation and for freight transport are taken directly from the literature. Additional context to these estimates is provided in the two right-most columns of the table (see Annex III, Section A.III.3 for data and assumptions on emission intensities and cost calculations and Annex II, Section A.II.3.1 for methodological issues on levelized cost metrics).

References: 1: IATA (2009), 2: TOSCA (2011), IEA (2009), 3: Dell'Olmo and Lulli (2003), Pyrialakou et al. (2012), 4: Bandivadekar (2008), ICCT (2010), Greene and Plotkin (2011), IEA (2012a), 5: IEA (2012), 6: NRC (2011a), 7: Sims et al. (2011), 8: Chandler et al. (2006), 9: ICCT (2010), NRC (2010), IEA (2012e), 10: ICCT. (2012), 11: NRC (2012), 12: UNEP (2011), 13: Chandler et al. (2006), IPCC (2007), AEA (2011), ITF (2011), IEA (2012d), 14: Hallmark et al. (2013), 15: Goodwin and Lyons (2010), Taylor and Philp (2010), Ashton-Graham et al. (2011), Höjer et al. (2011), Salter et al. (2011), Pandey (2006), 16: Behrendt et al. (2010), 17: Argonne National Lab. (2013), 18: UIC (2011), 19: IEA (2011a), 20: Crist (2009), IMO (2009), DNV (2010), ICCT (2011b), Lloyds Register and DNV (2011), Eide et al. (2011), 21: Crist (2009), 22: IMO (2009), 23: Lloyds Register and DNV (2011), 24: DNV (2010), 25: TIAX (2009), IEA (2012c), 26: Lawson et al. (2007), AEA (2011), 27: World Economic Forum/Accenture (2009), 28: Lawson et al. (2007), 29: TFL (2007), Eliasson (2008), Creutzig and He (2009), 30: IMO (2009), 31: Faber et al. (2012), 32: IEA (2009), IEA (2010b), 33: Bioenergy Annex, Chapter 11; 34: TOSCA (2011), 35: Marshall (2011), 36: ITDP (2009), 37: Maloni et al. (2013), 38: Andersson et al. (2011), 39: Wang (2012b), 40: Sælensminde (2004), 41: Tirachini and Hensher (2012), 42: DfT (2010), 43: Andersson et al. (2011), 44: Halzedine et al. (2009), 45: Sharpe (2010), 46: Skinner et al. (2010a), 47: Hill et al. (2012), 48: IEA (2012c), 49: Freight Transport Association (2013), 50: SAFED 2013; 51: NTM (2011), 52: Jardine (2009).

8.7 Co-benefits, risks and spillovers

Mitigation in the transport sector has the potential to generate synergies and co-benefits with other economic, social, and environmental objectives. In addition to mitigation costs (see Section 8.6), the deployment of mitigation measures will depend on a variety of other factors that relate to the broader objectives that drive policy choices. The implementation of policies and measures can have positive or negative effects on these other objectives—and vice versa. To the extent these effects are positive, they can be deemed as 'co-benefits'; if adverse and uncertain, they imply risks. Potential co-benefits and adverse side effects of alternative mitigation measures (Section 8.7.1), associated technical risks and uncertainties (Section 8.7.2), and public perceptions (Section 8.7.3) can significantly affect investment decisions and individual behaviour as well as influence the priority-setting of policymakers. Table 8.4 provides an overview of the potential co-benefits and adverse side-effects of the mitigation measures that are assessed in this chapter. In accordance with the three sustainable development pillars described in Sections 4.2 and 4.8, the table presents effects on objectives that may be economic, social, environmental, and health related. The extent to which co-benefits and adverse side effects will materialize in practice, and their net effect on social welfare, differ greatly across regions. Both are strongly dependent on local circumstances and implementation practices as well as on the scale and pace of the deployment of the different mitigation measures (see Section 6.6).

8.7.1 Socio-economic, environmental, and health effects

Transport relies almost entirely on oil with about 94% of transport fuels being petroleum products (IEA, 2011b). This makes it a key area of energy security concern. Oil is also a major source of harmful emissions that affect air quality in urban areas (see Section 8.2) (Sathaye et al., 2011). In scenario studies of European cities, a combination of public transit and cycling infrastructures, pricing, and land-use measures is projected to lead to notable co-benefits. These include improved energy security, reduced fuel spending, less congestion, fewer accidents, and increased public health from more physical activity, less air pollution and less noise-related stress (Costantini et al., 2007; Greene, 2010b; Rojas-Rueda et al., 2011; Rojas-Rueda et al., 2012; Creutzig et al., 2012a). However, only a few studies have assessed the associated welfare effects comprehensively and these are hampered by data uncertainties. Even more fundamental is the epistemological uncertainty attributed to different social costs. As a result, the range of plausible social costs and benefits can be large. For example, the social costs of the co-dimensions congestion, air pollution, accidents, and noise in Beijing were assessed to equate to between 7.5% to 15% of GDP (Creutzig and He, 2009). Improving energy security, mobility access, traffic congestion, public health, and safety are all important policy objectives that can possibly be influenced by mitigation actions (Jacobsen, 2003; Goodwin, 2004; Hultkrantz et al., 2006; Rojas-Rueda et al., 2011).

Energy security. Transport stands out in comparison to other energy end-use sectors due to its almost complete dependence on petroleum products (Sorrell and Speirs, 2009; Cherp et al., 2012). Thus, the sector suffers from both low resilience of energy supply and, in many countries, low sufficiency of domestic resources. (For a broader discussion on these types of concerns see Section 6.6.2.2). The sector is likely to continue to be dominated by oil for one or more decades (Costantini et al., 2007). For oil-importing countries, the exposure to volatile and unpredictable oil prices affects the terms of trade and their economic stability. Measuring oil independence is possible by measuring the economic impact of energy imports (Greene, 2010b). Mitigation strategies for transport (such as electrifying the sector and switching to biofuels) would decrease the sector's dependence on oil and diversify the energy supply, thus increasing resilience (Leiby, 2007; Shakya and Shrestha, 2011; Jewell et al., 2013). However, a shift away from oil could have implications for energy exporters (see Chapter 14). Additionally, mitigation measures targeted at reducing the overall transport demand—such as more compact urban form with improved transport infrastructure and journey distance reduction and avoidance (see Sections 8.4 and 12.4.2.1)—may reduce exposure to oil price volatility and shocks (Sovacool and Brown, 2010; Leung, 2011; Cherp et al., 2012).

Access and mobility. Mitigation strategies that foster multi-modality are likely to foster improved access to transport services particularly for the poorest and most vulnerable members of society. Improved mobility usually helps provide access to jobs, markets, and facilities such as hospitals and schools (Banister, 2011b; Boschmann, 2011; Sietchiping et al., 2012). More efficient transport and modal choice not only increases access and mobility it also positively affects transport costs for businesses and individuals (Banister, 2011b). Transport systems that are affordable and accessible foster productivity and social inclusion (Banister, 2008; Miranda and Rodrigues da Silva, 2012).

Employment impact. In addition to improved access in developing countries, a substantial number of people are employed in the formal and informal public transport sector (UN-Habitat, 2013). A shift to public transport modes is likely to generate additional employment opportunities in this sector (Santos et al., 2010). However, the net effect on employment of a shift towards low-carbon transport remains unclear (UNEP, 2011).

Traffic congestion. Congestion is an important aspect for decision makers, in particular at the local level, as it negatively affects journey times and creates substantial economic cost (Goodwin, 2004; Duranton and Turner, 2011). For example, in the United States in 2000, time lost in traffic amounted to around 0.7% of GDP (Federal Highway Administration, 2000) or approximately 85 billion USD_{2010}. This increased to

101 billion USD_{2010} in 2010, also being 0.7 % of GDP, but with more accurate data covering the cost per kilometre travelled of each major vehicle type for 500 urban centres (Schrank et al., 2011). Time lost was valued at 1.2 % of GDP in the UK (Goodwin, 2004); 3.4 % in Dakar, Senegal; 4 % in Manila, Philippines (Carisma and Lowder, 2007); 3.3 % to 5.3 % in Beijing, China (Creutzig and He, 2009); 1 % to 6 % in Bangkok, Thailand (World Bank, 2002) and up to 10 % in Lima, Peru where people on average spend around four hours in daily travel (JICA, 2005; Kunieda and Gauthier, 2007).

Modal shifts that reduce traffic congestion can simultaneously reduce GHG emissions and short-lived climate forcers. These include road congestion pricing, modal shifts from aviation to rail, and shifts from LDVs to public transport, walking, and cycling (Cuenot et al., 2012). However, some actions that seek to reduce congestion can induce additional travel demand, for example, expansions of airport infrastructure or construction of roads to increase capacity (Goodwin, 2004; ECMT, 2007; Small and van Dender, 2007).

Health. Exposure to vehicle exhaust emissions can cause cardiovascular, pulmonary, and respiratory diseases and several other negative health impacts (McCubbin, D.R., Delucchi, 1999; Medley et al., 2002; Chapters 7.9.2, 8.2, and WG II Chapter 11.9). In Beijing, for example, the social costs of air pollution were estimated to be as high as those for time delays from congestion (Creutzig and He, 2009). Various strategies to reduce fuel carbon intensity have varying implications for the many different air pollutants. For example, many studies indicate lower carbon monoxide and hydrocarbon emissions from the displacement of fossil-based transport fuels with biofuels, but NO_x emissions are often higher. Advanced biofuels are expected to improve performance, such as the low particulate matter emissions from ligno-cellulosic ethanol (see Hill et al., 2009, Sathaye et al., 2011 and Section 11.13.5). Strategies that target local air pollution, for example switching to electric vehicles, have the potential to also reduce CO2 emissions (Yedla et al., 2005) and black carbon emissions (UNEP and WMO, 2011) provided the electricity is sourced from low-carbon sources. Strategies to improve energy efficiency in the LDV fleet though fostering diesel-powered vehicles may affect air quality negatively (Kirchstetter et al., 2008; Schipper and Fulton, 2012) if not accompanied by regulatory measures to ensure emission standards remain stable. The structure and design of these strategies ultimately decides if this potential can be realized (see Section 8.2).

Transport also contributes to noise and vibration issues, which affect human health negatively (WHO, 2009; Oltean-Dumbrava et al., 2013; Velasco et al., 2013). Transport-related human inactivity has also been linked to several chronic diseases (WHO, 2008). An increase in walking and cycling activities could therefore lead to health benefits but conversely may also lead to an increase in traffic accidents and a larger lung intake of air pollutants (Kahn Ribeiro et al., 2012; Takeshita, 2012). Overall, the benefits of walking and cycling significantly outweigh the risks due to pollution inhalation (Rojas-Rueda et al., 2011; Rabl and de Nazelle, 2012).

Assessing the social cost of public health is a contested area when presented as disability-adjusted life years (DALYs). A reduction in CO_2 emissions through an increase in active travel and less use of ICE vehicles gave associated health benefits in London (7,332 DALYs per million population per year) and Delhi (12,516 (DALYs/million capita)/yr)—significantly more than from the increased use of lower-emission vehicles (160 (DALYs/million capita)/yr) in London, and 1,696 in Delhi) (Woodcock et al., 2009). More generally, it has been found consistently across studies and methods that public health benefits (induced by modal shift from LDVs to non-motorized transport) from physical activity outweighs those from improved air quality (Woodcock et al., 2009; de Hartog et al., 2010; Rojas-Rueda et al., 2011; Grabow et al., 2012; Maizlish et al., 2013). In a similar trend, reduced car use in Australian cities has been shown to reduce health costs and improve productivity due to an increase in walking (Trubka et al., 2010a).

Safety. The increase in motorized road traffic in most countries places an increasing incidence of accidents with 1.27 million people killed globally each year, of which 91 % occur in low and middle-income countries (WHO, 2011). A further 20 to 50 million people suffer serious injuries (WHO, 2011). By 2030, it is estimated that road traffic injuries will constitute the fifth biggest reason for premature deaths (WHO, 2008). Measures to increase the efficiency of the vehicle fleet can also positively affect the crash-worthiness of vehicles if more stringent safety standards are adopted along with improved efficiency standards (Santos et al., 2010). Lack of access to safe walking, cycling, and public transport infrastructure remains an important element affecting the success of modal shift strategies, in particular in developing countries (Sonkin et al., 2006; Tiwari and Jain, 2012).

Fossil fuel displacement. Economists have criticized the assumption that each unit of energy replaces an energy-equivalent quantity of fossil energy, leaving total fuel use unaffected (Drabik and de Gorter, 2011; Rajagopal et al., 2011; Thompson et al., 2011). As with other energy sources, increasing energy supply through the production of bioenergy affects energy prices and demand for energy services, and these changes in consumption also affect net global GHG emissions (Hochman et al., 2010; Rajagopal et al., 2011; Chen and Khanna, 2012). The magnitude of the effect of increased biofuel production on global fuel consumption is uncertain (Thompson et al., 2011) and depends on how the world responds in the long term to reduced petroleum demand in regions using increased quantities of biofuels. This in turn depends on the Organization of Petroleum Exporting Countries' (OPEC) supply response and with China's and India's demand response to a given reduction in the demand for petroleum in regions promoting biofuels, and the relative prices of biofuels and fossil fuels including from hydraulic fracturing (fracking) (Gehlhar et al., 2010; Hochman et al., 2010; Thompson et al., 2011). Notably, if the percentage difference in GHG emissions between an alternative fuel and the incumbent fossil fuel is less than the percentage rebound effect (the fraction not displaced, in terms of GHG emissions), a net increase in GHG emissions will result from promoting the alternative fuel, despite its nominally lower rating (Drabik and de Gorter, 2011).

Table 8.4 | Overview of potential co-benefits (green arrows) and adverse side effects (orange arrows) of the main mitigation measures in the transport sector. Arrows pointing up/down denote positive/negative effect on the respective objective/concern; a question mark (**?**) denotes an uncertain net effect. 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., energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. For possible upstream effects of low-carbon electricity and biomass supply, see Sections 7.9 as well as 11.7 and 11.13.6. Numbers in brackets correspond to references below the table.

Mitigation measures	**Effect on additional objectives/concerns**		
	Economic	**Social (including health)**	**Environmental**
Reduction of fuel carbon intensity: electricity, hydrogen, CNG, biofuels, and other fuels	↑ Energy security (diversification, reduced oil dependence and exposure to oil price volatility) (1–3,32–34,94) ↑ Technological spillovers (e.g., battery technologies for consumer electronics) (17,18,44,55,90)	Health impact via urban air pollution (59,69) by ? CNG, biofuels: net effect unclear (13,14,19,20,36,50) ↓ Electricity, hydrogen: reducing most pollutants (13,20,21,36,58,63,92) ↑ Shift to diesel: potentially increasing pollution (11,23,25) ↓ Health impact via reduced noise (electricity and fuel cell LDVs) (10,61,64–66,82) ↓ Road safety (silent electric LDVs at low speed) (56)	Ecosystem impact of electricity and hydrogen via: ↓ Urban air pollution (13,20,69,91–93) ↑ Material use (unsustainable resource mining) (17,18) ? Ecosystem impact of biofuels (24,41,42,89)
Reduction of energy intensity	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (1–3,32–34)	↓ Health impact via reduced urban air pollution (22,25,43,59,62,69,84) ↑ Road safety (crash-worthiness depending on the design of the standards) (38,39,52,60)	↓ Ecosystem and biodiversity impact via reduced urban air pollution (20,22,69,95)
Compact urban form and improved transport infrastructure **Modal shift**	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (77–80,86) ↑ Productivity (reduced urban congestion and travel times, affordable and accessible transport) (6–8,26,35,45,46,48,49) ? Employment opportunities in the public transport sector vs. car manufacturing jobs (38,76,89)	Health impact for non-motorized modes via ↓ Increased physical activity (7,12,27,28,29,51,64,70,73,74) ↑ Potentially higher exposure to air pollution (19,27,59,69,70,74) ↓ Noise (modal shift and travel reduction) (58,61,64–66,81–83) ↑ Equitable mobility access to employment opportunities, particularly in developing countries (4,5,8,9,26,43,47,49) ↑ Road safety (via modal shift and/or infrastructure for pedestrians and cyclists) (12,27,37,39,40,87,88)	Ecosystem impact via ↓ Urban air pollution (20,54,58,60,69) ↓ Land-use competition (7,9,58,71,75)
Journey distance reduction and avoidance	↑ Energy security (reduced oil dependence and exposure to oil price volatility) (31,77–80,86) ↑ Productivity (reduced urban congestion, travel times, walking) (6–8,26,45,46,49)	↓ Health impact (for non-motorized transport modes) (7,12,22,27–30,67,68,72,75)	Ecosystem impact via ↓ Urban air pollution (20,53,54,60,69) ↑ New/shorter shipping routes (15,16,57) ↓ Land-use competition from transport infrastructure (7,9,58,71,75)

References: 1: Greene (2010b), 2: Costantini et al. (2007), 3: Bradley and Lefevre (2006), 4: Boschmann (2011), 5: Sietchiping et al. (2012), 6: Cuenot et al. (2012), 7: Creutzig et al. (2012a), 8: Banister (2008), 9: Geurs and Van Wee (2004), Banister (2008), 10: Creutzig and He (2009), 11: Leinert et al. (2013), 12: Rojas-Rueda et al. (2011), 13: Sathaye et al. (2011), 14: Hill et al. (2009), 15: Garneau et al. (2009), 16: Wassmann (2011), 17: Eliseeva and Bünzli (2011), 18: Massari and Ruberti (2013), 19: Takeshita (2012), 20: Kahn Ribeiro et al. (2012), 21: IEA (2011a), 22: Woodcock et al. (2009), 23: Schipper and Fulton (2012), 24: see Section 11.13.6, 25: Kirchstetter et al. (2008), 26: Banister (2008), Miranda and Rodrigues da Silva (2012), 27: Rojas-Rueda et al. (2011), Rabl and de Nazelle (2012), 28: Jacobsen (2003), 29: Hultkrantz et al. (2006), 30: Goodwin (2004), 31: Sorrell and Speirs (2009), 32: Jewell et al. (2013), 33: Shakya and Shrestha (2011), 34: Leiby (2007), 35: Duranton and Turner (2011), 36: Trubka et al. (2010a), 37: WHO (2011), 38: Santos et al. (2010), 39: Tiwari and Jain (2012), 40: Sonkin et al. (2006), 41: Chum et al. (2011), 42: Larsen et al. (2009), 43: Steg and Gifford (2005), 44: Christensen et al. (2012), 45: Schrank et al. (2011), 46: Carisma and Lowder (2007), 47: World Bank (2002), 48: JICA (2005), 49: Kunieda and Gauthier (2007), 50: see Section 11.13.5, 51: Maizlish et al. (2013), 52: WHO (2008), 53: ICCT (2012b), 54: Yedla et al. (2005), 55: Lu et al. (2013), 56: Schoon and Huijskens (2011), 57: see Section 8.5, 58: see Section 12.8, 59: Medey et al. (2002), 60: Machado-Filho (2009), 61: Milner et al. (2012), 62: Kim Oanh et al. (2012), 63: Fulton et al. (2013), 64: de Nazelle et al. (2011), 65: Twardella and Ndrepepa (2011), 66: Kawada (2011), 67: Grabow et al. (2012), 68: Pucher et al. (2010), 69: Section 7.9.2 and WGII Section 11.9, 70: de Hartog et al. (2010), 71: Heath et al. (2006), 72: Saelens et al. (2003), 73: Sallis et al. (2009), 74: Hankey and Brauer (2012), 75: Cervero and Sullivan (2011). 76: Mikler (2010), 77: Cherp et al. (2012), 78: Leung (2011), 79: Knox-Hayes et al. (2013), 80: Sovacool and Brown (2010), 81: WHO (2009), 82: Oltean-Dumbrava et al. (2013), 83: Velasco et al. (2013), 84: Smith et al. (2013), 86: see Section 8.4, 87: Schepers et al. (2013), 88: White (2004), 89: UNEP/GEF (2013), 90: Rao and Wang (2011), 91: Notter et al. (2010), 92: Sioshansi and Denholm (2009), 93: Zackrisson et al. (2010), 94: Michalek et al. (2011), 95: see Section 8.2.2.1.

If biofuels displace high carbon-intensity oil from tar sands or heavy oils, the displacement effect would provide higher GHG emission savings. Estimates of the magnitude of the petroleum rebound effect cover a wide range and depend on modelling assumptions. Two recent modelling studies suggest that biofuels replace about 30–70 % of the energy equivalent quantity of petroleum-based fuel (Drabik and de Gorter, 2011; Chen and Khanna, 2012), while others find replacement can be as low as 12–15 % (Hochman et al., 2010). Under other circumstances, the rebound can be negative. The rebound effect is always subject to the policy context, and can be specifically avoided by global cap and pricing instruments.

8.7.2 Technical risks and uncertainties

Different de-carbonization strategies for transport have a number of technological risks and uncertainties associated with them. Unsustainable mining of resources to supply low-carbon transport technologies such as batteries and fuel cells may create adverse side effects for the local environment (Massari and Ruberti, 2013; Eliseeva and Bünzli, 2011). Mitigation options from lower energy-intensity technologies (e.g., electric buses) and reduced fuel carbon intensity (e.g., biofuels) are particularly uncertain regarding their technological viability, sources of primary energy, and biomass and lifecycle emission reduction potential (see Section 8.3). Biofuels indicators are being developed to ensure a degree of sustainability in their production and use (UNEP/GEF, 2013; Sections 11.13.6 and 11.13.7). For shipping, there is potential for new and shorter routes such as across the Arctic, but these may create risks to vulnerable ecosystems (see Section 8.5).

A focus on improving vehicle fuel efficiency may reduce GHG emissions and potentially improve air quality, but without an increase in modal choice it may not result in improved access and mobility (Steg and Gifford, 2005). The shift toward more efficient vehicles, for example the increasing use of diesel for the LDV fleet in Europe, has also created tradeoffs such as negatively affecting air quality in cities (Kirchstetter et al., 2008). More generally, mitigation options are also likely to be subject to rebound effects to varying degrees (see Sections 8.3 and 8.10).

8.7.3 Technological spillovers

Advancements in technologies developed for the transport sector may have technological spillovers to other sectors. For example advancements in battery technology systems for consumer electronics could facilitate the development of batteries for electric vehicles and vice-versa (Rao and Wang, 2011). The production of land-competitive biofuels can also have direct and indirect effects on biodiversity, water, and food availability (see Sections 11.13.6 and 11.13.7). Other areas where technological spillovers may occur include control and navigation systems and other information technology applications.

8.8 Barriers and opportunities

Barriers and opportunities are processes that hinder or facilitate deployment of new transport technologies and practices. Reducing transport GHG emissions is inherently complex as increasing mobility with LDVs, HDVs, and aircraft has been associated with increasing wealth for the past century of industrialization (Meyer et al., 1965; Glaeser, 2011). The first signs of decoupling fossil fuel-based mobility from wealth generation are appearing in OECD countries (Kenworthy, 2013). To decouple and reduce GHG emissions, a range of technologies and practices have been identified that are likely to be developed in the short- and long-terms (see Section 8.3), but barriers to their deployment exist as do opportunities for those nations, cities, and regions willing to make low-carbon transport a priority. There are many barriers to implementing a significantly lower carbon transport system, but these can be turned into opportunities if sufficient consideration is given and best-practice examples are followed.

8.8.1 Barriers and opportunities to reduce GHGs by technologies and practices

The key transport-related technologies and practices garnered from sections above are set out below in terms of their impact on fuel carbon intensity, improved energy intensity of technologies, system infrastructure efficiency, and transport demand reduction. Each has short- and long-term potentials to reduce transport GHG emissions that are then assessed in terms of their barriers and opportunities (Table 8.5). (Details of policies follow in Section 8.10).

Psychological barriers can impede behavioural choices that might otherwise facilitate mitigation as well as adaptation and environmental sustainability. Many individuals are engaged in ameliorative actions to improve their local environment, although many could do more. Gifford (2011) outlined barriers that included "limited cognition about the problem, ideological worldviews that tend to preclude pro-environmental attitudes and behaviour, comparisons with the responses of other people, sunk costs and behavioural momentum, a dis-credence toward experts and authorities, perceived risks as a result of making change and positive but inadequate confidence to make behavioural change."

The range of barriers to the ready adoption of the above technologies and practices have been described in previous sections, but are summarized in Table 8.5 along with the opportunities available. The challenges involved in removing barriers in each of the 16 elements listed depend on the politics of a region. In most places, reducing fuel carbon and energy intensities are likely to be relatively easy as they are technology-based, though they can meet capital investment barriers in developing regions and may be insufficient in the longer-term. On the other hand, system infrastructure efficiency and transport demand reduction options would require human interventions and social change as well as public investment. Although these may not require as much capital investment, they would still require public acceptance of any transport policy option (see Section 8.10). As implementation approaches, public acceptance fluctuates, so political support may be required at critical times (Pridmore and Miola, 2011).

Table 8.5 | Transport technologies and practices with potential for both short- and long-term GHG reduction and the related barriers and opportunities in terms of the policy arenas of fuel carbon intensity, energy intensity, infrastructure, and activity.

Transport technology or practice	Short-term possibilities	Long-term possibilities	Barriers	Opportunities	References
Fuel carbon intensity: fuel switching *BEV—Battery electric vehicle; PHEV—Plug-in hybrid electric vehicle; FCV—Fuel cell vehicles; CHP—combined heat and power; CNG—Compressed natural gas; LNG—Liquefied natural gas; CBG—Compressed biogas; LBG—Liquefied biogas)*					
1. BEVs and PHEVs based on renewable electricity.	Rapid increase in use likely over next decade from a small base, so only a small impact likely in short-term.	Significant replacement of ICE-powered LDVs.	EV and battery costs reducing but still high. Lack of infrastructure, and recharging standards not uniform. Vehicle range anxiety. Lack of capital and electricity in some least developed countries.	Universal standards adopted for EV rechargers. Demonstration in green city areas with plug-in infrastructure. Decarbonized electricity. Smart grids based on renewables. EV subsidies. New business models, such as community car sharing.	EPRI 2008; Beck ,2009; IEA, 2011; Salter et al., 2011; Kley et al., 2011; Leurent & Windisch, 2011; Graham-Rowe et al., 2012
2. CNG, LNG, CBG and LBG displacing gasoline in LDVs and diesel in HDVs.	Infrastructure available in some cities so can allow a quick ramp–up of gas vehicles in these cities.	Significant replacement of HDV diesel use depends on ease of engine conversion, fuel prices and extent of infrastructure.	Insufficient government programmes, conversion subsidies and local gas infrastructure and markets. Leakage of gas.	Demonstration gas conversion programmes that show cost and health co-benefits. Fixing gas leakage in general.	IEA, 2007; Salter et al., 2011; Alvarez et al., 2012
3. Biofuels displacing gasoline, diesel and aviation fuel.	Niche markets continue for first generation biofuels (3 % of liquid fuel market, small biogas niche markets).	Advanced and drop-in biofuels likely to be adopted around 2020–2030, mainly for aviation.	Some biofuels can be relatively expensive, environmentally poor and cause inequalities by inducing increases in food prices.	Drop-in fuels attractive for all vehicles. Biofuels and bio-electricity can be produced together, e.g., sugarcane ethanol and CHP from bagasse. New biofuel options need to be further tested, particularly for aviation applications.	Ogden et al., 2004; Fargione et al., 2010; IEA, 2010; Plevin et al., 2010; Creutzig et al., 2011; Salter et al., 2011; Pacca and Moreira, 2011; Flannery et al., 2012
Energy intensity: efficiency of technologies *FEV—fuel efficient vehicles ICE—internal combustion engine*					
4. Improved vehicle ICE technologies and on-board information and communication technologies (ICT) in fuel-efficient vehicles.	Continuing fuel efficiency improvements across new vehicles of all types can show large, low-cost, near-term reductions in fuel demand.	Likely to be a significant source of reduction. Behavioural issues (e.g., rebound effect). Consumer choices can reduce vehicle efficiency gains.	Insufficient regulatory support for vehicle emissions standards. On-road performance deteriorates compared with laboratory tests.	Creative regulations that enable quick changes to occur without excessive costs on emissions standards. China and most OECD countries have implemented standards. Reduced registration tax can be implemented for low CO_2eq-based vehicles.	Schipper et al., 2000; Ogden et al., 2004; Small and van Dender, 2007; Sperling and Gordon, 2009; Timilsina and Dulal, 2009; Fuglestvedt et al., 2009; Mikler, 2010; Salter et al., 2011
Structure: system infrastructure efficiency					
5. Modal shift by public transport displacing private motor vehicle use.	Rapid short-term growth already happening.	Significant displacement only where quality system infrastructure and services are provided.	Availability of rail, bus, ferry, and other quality transit options. Density of people to allow more access to services. Levels of services. Time barriers on roads without right of way Public perceptions.	Investment in quality transit infrastructure, density of adjacent land use, and high level of services using innovative financing that builds in these features. Multiple co-benefits especially where walkability health benefits are a focus.	Kenworthy, 2008; Millard-Ball & Schipper, 2011; Newman and Kenworthy, 2011; Salter et al., 2011; Buehler and Pucher, 2011; Newman and Matan, 2013

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Transport technology or practice	Short-term possibilities	Long-term possibilities	Barriers	Opportunities	References
6. Modal shift by cycling displacing private motor vehicle use.	Rapid short-term growth already happening in many cities.	Significant displacement only where quality system infrastructure is provided.	Cultural barriers and lack of safe cycling infrastructure and regulations. Harsh climate.	Demonstrations of quality cycling infrastructure including cultural programmes and bike-sharing schemes.	Bassett et al., 2008; Garrard et al., 2008; Salter et al., 2011; Anon, 2012; Sugiyama et al., 2012
7. Modal shift by walking displacing private motor vehicle use.	Some growth but depends on urban planning and design policies being implemented.	Significant displacement where large-scale adoption of polycentric city policies and walkable urban designs are implemented.	Planning and design policies can work against walkability of a city by too easily allowing cars into walking city areas. Lack of density and integration with transit. Culture of walkability.	Large-scale adoption of polycentric city policies and walkable urban designs creating walking city in historic centres and new ones. Cultural programmes.	Gehl, 2011; Höjer et al., 2011; Leather et al., 2011; Salter et al., 2011
8. Urban planning by reducing the distances to travel within urban areas.	Immediate impacts where dense transit-oriented development (TOD) centres are built.	Significant reductions where widespread polycentric city policies are implemented.	Urban development does not always favour dense TOD centres being built. TODs need quality transit at their base. Integration of professional areas required.	Widespread polycentric city policies implemented with green TODs, backed by quality transit. Multiple co-benefits in sprawl costs avoided and health gains.	Anon, 2004; Anon, 2009; Naess, 2006; Ewing et al., 2008; Cervero and Murakami, 2009; Cervero and Murakami, 2010; Cervero and Sullivan, 2011; Salter et al., 2011; Lefèvre; 2009
9. Urban planning by reducing private motor vehicle use through parking and traffic restraint.	Immediate impacts on traffic density observed.	Significant reductions only where quality transport alternatives are available.	Political barriers due to perceived public opposition to increased costs, traffic and parking restrictions. Parking codes too prescriptive for areas suited to walking and transit.	Demonstrations of better transport outcomes from combinations of traffic restraint, parking and new transit/walking infrastructure investment.	Gwilliam, 2003; ADB, 2011; Creutzig et al., 2011; Shoup, 2011; Newman and Matan, 2013
10. Modal shift by displacing aircraft and LDV trips through high-speed rail alternatives.	Immediate impacts after building rail infrastructure.	Continued growth but only short-medium distance trips suitable.	High-speed rail infrastructure expensive.	Demonstrations of how to build quality fast-rail using innovative finance.	Park and Ha, 2006; Gilbert and Perl, 2010; Åkerman, 2011; Salter et al., 2011
11. Modal shift of freight by displacing HDV demand with rail.	Suitable immediately for medium- and long-distance freight and port traffic.	Substantial displacement only if large rail infrastructure improvements made, the external costs of freight transport are fully internalized, and the quality of rail services are enhanced. EU target to have 30 % of freight tonne-km moving more than 300 km to go by rail (or water) by 2030.	Inadequacies in rail infrastructure and service quality. Much freight moved over distances that are too short for rail to be competitive.	Upgrading of inter-modal facilities. Electrification of rail freight services. Worsening traffic congestion on road networks and higher fuel cost will favour rail.	IEA, 2009; Schiller et al., 2010; Salter et al., 2011
12. Modal shift by displacing truck and car use through waterborne transport.	Niche options already available. EU "Motorways of the Sea" programme demonstrates potential to expand short-sea shipping share of freight market.	Potential to develop beyond current niches, though will require significant investment in new vessels and port facilities.	Lack of vision for water transport options and land-locked population centres. Long transit times. Tightening controls on dirty bunker fuel and SO_x and NO_x emissions raising cost and reducing modal competitiveness.	Demonstrations of quality waterborne transport that can be faster and with lower-carbon emissions than alternatives.	Fuglestvedt et al., 2009; Salter et al. 2011
13. System optimization by improved road systems, freight logistics and efficiency at airports and ports.	Continuing improvements showing immediate impacts.	Insufficient in long term to significantly reduce carbon emissions without changing mode, reducing mobility, or reducing fuel carbon intensity.	Insufficient regulatory support and key performance indicators (KPIs) covering logistics and efficiency.	Creative regulations and KPIs that enable change to occur rapidly without excessive costs.	Pels and Verhoef, 2004; A. Zhang and Y. Zhang, 2006; Fuglestvedt et al., 2009; Kaluza et al., 2010; McKinnon, 2010; Simaiakis and Balakrishnan, 2010; Salter et al., 2011
Activity: demand reduction					
14. Mobility service substitution by reducing the need to travel through enhanced communications.	Niche markets growing and ICT improving in quality and reliability.	Significant reductions possible after faster broadband and quality images available, though ICT may increase the need for some trips.	Technological barriers due to insufficient broadband in some regions.	Demonstrations of improved video-conferencing system quality.	Golob and Regan, 2001; Choo et al., 2005; Wang and Law, 2007; Yi and Thomas, 2007; Zhen et al., 2009; Salter et al., 2011; Mokhtarian and Meenakshisundaram, 2002

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Transport technology or practice	Short-term possibilities	Long-term possibilities	Barriers	Opportunities	References
15. Behavioural change from reducing private motor vehicle use through pricing policies, e.g, network charges and parking fees.	Immediate impacts on traffic density observed.	Significant reductions only where quality transport alternatives are available.	Political barriers due to perceived public opposition to increased pricing costs. Lack of administrative integration between transport, land-use and environment departments in city municipalities.	Demonstrations of better transport outcomes from combinations of pricing, traffic restraint, parking and new infrastructure investment from the revenue. Removing subsidies to fossil fuels important for many co-benefits.	Litman, 2005, 2006; Salter et al., 2011; Creutzig et al., 2012a
16. Behavioural change resulting from education to encourage gaining benefits of less motor vehicle use.	Immediate impacts of 10–15 % reduction of LDV use are possible.	Significant reductions only where quality transport alternatives are available.	Lack of belief by politicians and professionals in the value of educational behaviour change programmes.	Demonstrations of 'travel smart' programmes linked to improvements in sustainable transport infrastructure. Cost effective and multiple co-benefits.	Pandey, 2006; Goodwin and Lyons, 2010; Taylor and Philp, 2010; Ashton-Graham et al., 2011; Höjer et al., 2011; Salter et al., 2011

8.8.2 Financing low-carbon transport

Transport is a foundation for any economy as it enables people to be linked, goods to be exchanged, and cities to be structured (Glaeser, 2011). Transport is critical for poverty reduction and growth in the plans of most regions, nations, and cities. It therefore is a key area to receive development funding. In past decades the amount of funding going to transport through various low-carbon mechanisms had been relatively low, but has had a recent increase. The projects registered in the United Nations Environmental Programme (UNEP) pipeline database for the clean development mechanism (CDM) shows only 42 projects out of 6707 were transport-related (Kopp, 2012). The Global Environment Facility (GEF) has approved only 28 projects in 20 years, and the World Bank's Clean Technology Fund has funded transport projects for less than 17 % of the total. If this international funding does not improve, then transport could move from emitting 22 % of energy-related GHGs in 2009 to reach 80 % by 2050 (ADB, 2012a). Conversely, national appropriate mitigation measures (NAMAs) could attract low-carbon financing in the transport area for the developing world. To support sustainable transport system development, eight multi-lateral development banks have pledged to invest around 170 billion USD_{2010} over the next ten years (Marton-Lefèvre, 2012).

A major part of funding sustainable transport could arise from the redirection of funding from unsustainable transport (Sakamoto et al., 2010; UNEP, 2011; ADB, 2012b). In addition, land-based taxes or fees can capitalize on the value gains brought by sustainable transport infrastructures (Chapter 12.5.2). For example, in locations close to a new rail system, revenue can be generated from land-based taxes and council rates levied on buildings that are seen to rise by 20–50 % compared to areas not adjacent to such an accessible facility (Cervero 1994; Haider and Miller, 2000; Rybeck, 2004). Local municipal financing by land value capture and land taxes could be a primary source of financing for public transit and non-motorized transport infrastructure, especially in rapidly urbanizing Asia (Chapter 12.5.2; Bongardt et al., 2013). For example, a number of value capture projects are underway as part of the rapid growth in urban rail systems, including Indian cities (Newman et al., 2013). The ability to fully outline the costs and benefits of low-carbon transport projects will be critical to accessing these new funding opportunities. R&D barriers and opportunities exist for all of these agendas in transport.

8.8.3 Institutional, cultural, and legal barriers and opportunities

Institutional barriers to low-carbon transport include international standards required for new EV infrastructure to enable recharging; low pricing of parking; lack of educational programmes for modal shift; and polycentric planning policies that require the necessary institutional structures (OECD, 2012; Salter et al., 2011). Cultural barriers underlie every aspect of transport, for example, automobile dependence being built into a culture and legal barriers that can exist to prevent the building of dense, mixed-use community centres that reduce car dependence. Overall, there are political barriers that combine most of the above (Pridmore and Miola, 2011).

Opportunities also exist. Low-carbon transport elements in green growth programmes (OECD, 2011; Hargroves and Smith, 2008) are likely to be the basis of changing economies because they shape cities and create wealth (Glaeser, 2011; Newman et al., 2009). Those nations, cities, businesses, and communities that grasp the opportunities to demonstrate these changes are likely to be the ones that benefit most in the future (OECD, 2012). The process of decoupling economic growth from fossil fuel dependence could become a major feature of the future economy (ADB, 2012a) with sustainable transport being one of four key approaches. Overcoming the barriers to each technology and practice (Table 8.5) could enable each to contribute to a more sustainable transport system and realize the opportunities from technological and social changes when moving towards a decarbonized economy of the future.

8.9 Sectoral implications of transformation pathways and sustainable development

Scenarios that focus on possible reductions of energy use and CO_2 emissions from transport are sourced from either integrated models that incorporate a cross-sector approach to modelling global emissions reductions and other mitigation options, or sectoral models that focus solely on transport and its specific potential for emissions reductions. A comparison of scenarios from both integrated and sectoral models with a focus on long-term concentration goals up until 2100 is conducted in this section. This comparison is complemented by the results of the transport-specific evaluation of cost and potentials in Section 8.6 and supported by a broader integrated assessment in Chapter 6[7].

The integrated and sectoral model transport literature presents a wide range of future CO_2 emissions reduction scenarios and offers two distinct forms of assessment. Both contemplate how changes in passenger and freight activity, structure, energy intensity, and fuel carbon intensity could each contribute to emissions reductions and assist the achievement of concentration goals.

The integrated model literature focuses upon systemic assessments of the impacts of macro-economic policies (such as limits on global/regional emissions or the implementation of a carbon tax) and reviews the relative contributions of a range of sectors to overall global mitigation efforts (Section 6.2.1). Within the WG III AR5 Scenario Database (Annex II.10), transport specific variables are not available for all scenarios. Therefore, the present analysis is based on a sub-sample of almost 600 scenarios[8]. Due to the macro-economic scale of their analysis, integrated models have a limited ability to assess behaviour changes that may result from structural developments impacting on modal shift or journey avoidance, behavioural factors such as travel time and budget might contribute up to 50 % reduction of activity globally in 2100 compared to the 2005 baseline (Girod et al., 2013).

Sectoral scenarios, however, are able to integrate results concerning emission reduction potentials from sector specific interventions (such as vehicle taxation, parking fees, fuel economy standards, promotion of modal shift, etc.). They can be instrumental in evaluating how policies that target structural factors[9] can impact on passenger and freight travel demand reductions (see Sections 8.4 and 8.10). Unlike integrated models, sectoral studies do not attempt to measure transport emissions reductions with respect to the amounts that other sectors could contribute in order to reach long-term concentration goals.

8.9.1 Long term stabilization goals—integrated and sectoral perspectives

A diversity of transformation pathways highlights the possible range of decarbonization options for transport (Section 6.8). Results from both integrated and sectoral models up until 2050 closely match each other. Projected GHG emissions vary greatly in the long term integrated scenarios, reflecting a wide range in assumptions explored such as future population, economic growth, policies, technology development, and acceptance (Section 6.2.3). Without policy interventions, a continuation of current travel demand trends could lead to a more than doubling of transport-related CO_2 emissions by 2050 and more than a tripling by 2100 in the highest scenario projections (Figure 8.9). The convergence of results between integrated and sectoral model studies suggests that through substantial, sustained, and directed policy interventions, transport emissions can be consistent with limiting long-term concentrations to 430–530 ppm CO_2eq.

The growth of global transport demand could pose a significant challenge to the achievement of potential emission reduction goals. The average transport demand growth from integrated scenarios with respect to 2010 levels suggests that total passenger and freight travel will continue to grow in the coming decades up to 2050, with most of this growth taking place within developing country regions where large shares of future population and income growth are expected (Figure 8.10) (UN Secretariat, 2007).

A positive income elasticity and the relative price-inelastic nature of passenger travel partially explain the strength of the relationship between travel and income (Dargay, 2007; Barla et al., 2009). Both integrated and sectoral model projections for total travel demand show that while demand in non-OECD countries grows rapidly, a lower starting point results in a much lower per capita level of passenger travel in 2050 than in OECD countries (Figure 8.10) (IEA, 2009; Fulton

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[7] Section 6.2.2 and Annex II.10 provide details on the WG III AR5 Scenario Database, which is the source of more than 1,200 integrated scenarios.

[8] This section builds upon the scenarios which were collated by Chapter 6 in the WG III AR5 Scenario Database and compares them to global scale transport studies. The scenarios were grouped into baseline and mitigation scenarios. As described in more detail in Chapter 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. 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 ppm CO_2eq, 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. 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 (Chapter 6.3.2). The x-axis of Figures 8.9 to 8.12 show specific sample numbers for each category of scenario reviewed.

[9] These include land use planning that favours high density or polycentric urban forms; public transport oriented developments with mixed uses; and high quality city environments.

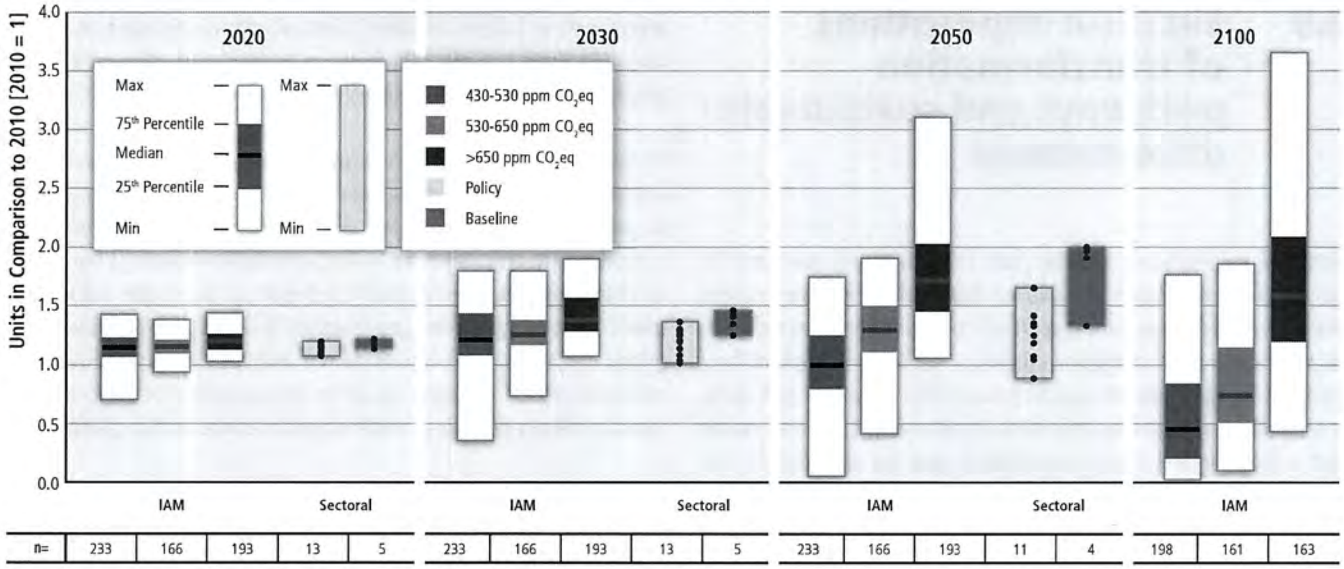

Figure 8.9 | Direct global transport CO_2 emissions. All results for passenger and freight transport are indexed relative to 2010 values for each scenario from integrated models grouped by CO_2eq concentration levels by 2100, and sectoral studies grouped by baseline and policy categories. Sources: Integrated models—WG III AR5 Scenario Database (Annex II.10). Sectoral models: IEA (2008, 2011b, 2012b), WEC (2011a), EIA (2011), IEEJ (2011).

Note: All figures in Section 8.9 show the full range of results for both integrated and sectoral studies. Where the data is sourced from the WG III AR5 Scenario Database a line denotes the median scenario and a box and bolder colours highlight the inter-quartile range. The specific observations from sectoral studies are shown as black dots with light bars (policy) or dark bars (baseline) to give the full ranges. "n" equals number of scenarios assessed in each category.

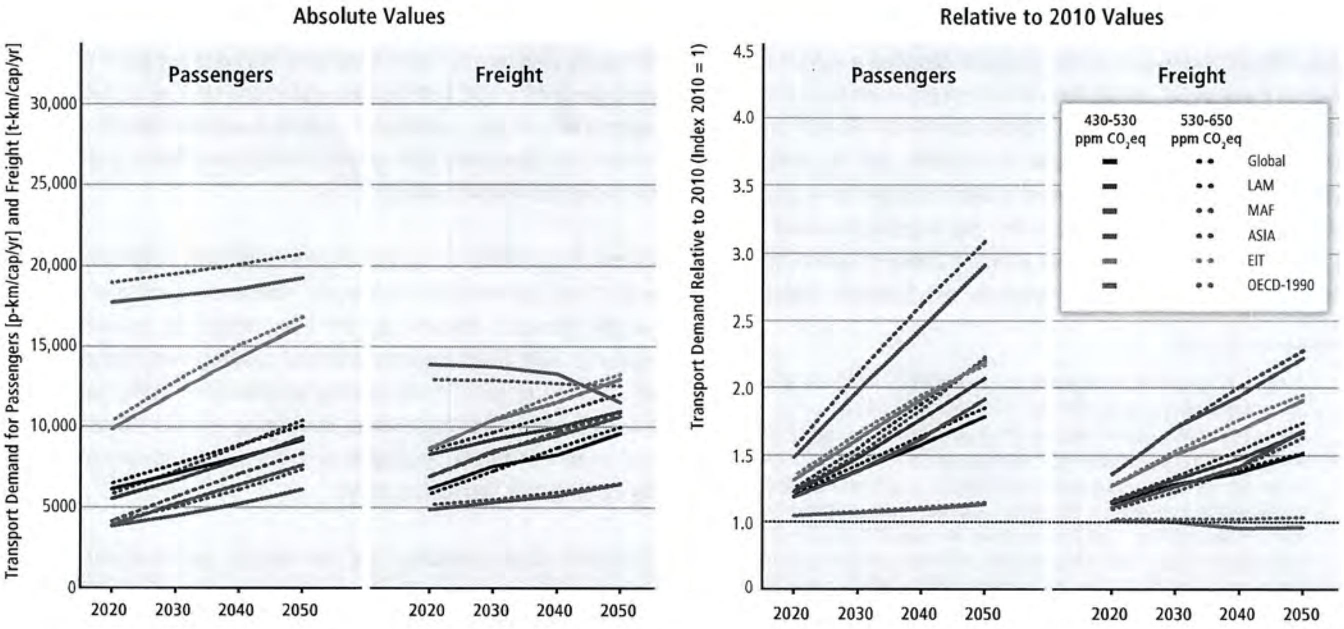

Figure 8.10 | Global passenger (p-km/capita/yr) and freight (t-km/capita/yr) regional demand projections out to 2050 based on integrated models for various CO_2eq concentration levels by 2100—with normalized values highlighting growth and controlling differences in base year values across models. Source: WG III AR5 Scenario Database (Annex II.10).

et al., 2013). Consistent with a recent decline in growth of LDV use in some OECD countries (Goodwin and Van Dender, 2013), integrated and sectoral model studies have suggested that decoupling of passenger transport from GDP could take place after 2035 (IEA, 2012; Girod et al., 2012). However, with both transport demand and GDP tied to population growth, decoupling may not be fully completed. At higher incomes, substitution to faster travel modes, such as fast-rail and air travel, explains why total passenger and freight travel continues to rise faster than per capita LDV travel (Schäfer et al., 2009).

Freight transport increases in all scenarios at a slower pace than passenger transport, but still rises as much as threefold by 2050 in comparison to 2010 levels. Freight demand has historically been closely coupled to GDP, but there is potential for future decoupling. Over the long term, changes in activity growth rates (with respect to 2010) for 430–530 ppm CO_2eq scenarios from integrated models suggest that decoupling freight transport demand from GDP can take place earlier than for passenger travel. Modest decreases in freight activity per dollar of GDP suggest that a degree of relative decoupling between freight and income has been occurring across developed countries including Finland (Tapio, 2005), the UK (McKinnon, 2007a) and Denmark (Kveiborg and Fosgerau, 2007). Two notable exceptions are Spain and South Korea, which are at relatively later stages of economic development (Eom et al., 2012). Where decoupling has occurred, it is partly associated with the migration of economic activity to other countries (Corbertt and Winebrake, 2008; Corbertt and Winebrake, 2011). See Sections 3.9.5 and 5.4.1 for a broader discussion of leakage. Opportunities for decoupling could result from a range of changes, including a return to more localized sourcing (McKinnon, 2007b); a major shift in the pattern of consumption to services and products of higher value; the digitization of media and entertainment; and an extensive application of new transport-reducing manufacturing technologies such as 3-D printing (Birtchnell et al., 2013).

Due to the increases in total transport demand, fuel consumption also increases over time, but with GHG emissions at a lower level if policies toward decarbonization of fuels and reduced energy intensity of vehicles are successfully implemented. The integrated scenarios suggest that energy intensity reductions for both passenger and freight transport could continue to occur if the present level of fuel economy standards are sustained over time, or could decrease further with more stringent concentration goals (Figure 8.11).

Projected reductions in energy intensity for freight transport scenarios (EJ/bn t-km) in the scenarios show a wider spread (large ranges in Figure 8.11 between the 25th and 75th percentiles) than for passengers, but still tend to materialize over time. Aviation and road transport have higher energy intensities than rail and waterborne transport (Figure 8.6). Therefore, they account for a larger share of emissions than their share of meeting service demands (Girod et al., 2013). However, limited data availability makes the assessment of changes in modal structure challenging as not all integrated models provide information at a sufficiently disaggregated level or fully represent structural and behavioural choices. Sectoral studies suggest that achieving significant reductions in aviation emissions will require reductions in the rate of growth of travel activity through demand management alongside technological advances (Bows et al., 2009).

In addition to energy intensity reductions, fuel carbon intensity can be reduced further in stringent mitigation scenarios and play an important role in the medium term with the potential for continued improvement throughout the century (Figure 8.11). Scenarios suggest that fuel switch-

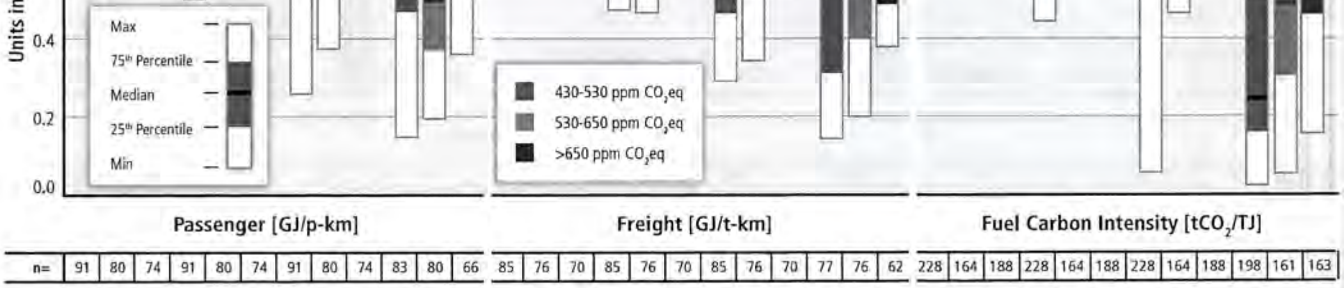

Figure 8.11 | Normalized energy intensity scenarios (indexed relative to 2010 values) out to 2100 for passenger (left panel) and freight transport (centre panel), and for fuel carbon intensity based on scenarios from integrated models grouped by CO_2eq concentration levels by 2100 (right panel). Source: WG III AR5 Scenario Database (Annex II.10). Note "n" equals number of scenarios assessed in each category.

ing does not occur to a great extent until after 2020–2030 (Fig 8.12) after which it occurs sooner in more stringent concentration scenarios. The mix of fuels and technologies is difficult to foresee in the long term, especially for road transport, but liquid petroleum fuels tend to dominate at least up until 2050 even in the most stringent mitigation scenario. Within some sectoral studies, assumed breakthroughs in biofuels, fuel cell vehicles, and electrification of road vehicles help achieve deep reductions in emissions by 2050 (Kahn Ribeiro et al., 2012; Williams et al., 2012). Other studies are less confident about fuel carbon intensity reductions, arguing that advanced biofuels, low-carbon electricity, and hydrogen will all require time to make substantial contributions to mitigation efforts. They therefore attribute greater potential for emission reductions to structural and behavioural changes (Salter et al., 2011).

Model assumptions for future technology cost, performance, regulatory environment, consumer choice, and fuel prices result in different shares of fuels that could replace fossil fuels (Table 8.3; Krey and Clarke, 2011). Availability of carbon dioxide capture and storage (CCS) is also likely to have major impact on fuel choices (Luckow et al., 2010; Sathaye et al., 2011). Uncertainty is evident by the wide ranges in all the pathways considered, and are larger after 2050 (Bastani et al., 2012; Wang et al., 2012; Pietzcker et al., 2013). In terms of direct emissions reductions, biofuels tend to have a more important role in the period leading up to 2050. In general, integrated models have been criticized as being optimistic on fuel substitution possibilities, specifically with respect to lifecycle emission assumptions and hence the utilization of biofuels (Sections 8.3 and 11.A.4; Creutzig et al., 2012a; Pietzcker et al., 2013). However, scenarios from integrated models are consistent with sectoral scenarios with respect to fuel shares in 2050 (Figure 8.12). Within the integrated model scenarios, deeper emissions reductions associated with lower CO_2eq concentrations in 2100 are consistent with increasing market penetration of low-carbon electricity and hydrogen in the latter part of the century. Uncertainties as to which fuel becomes dominant, as well as on the role of energy efficiency improvements and fuel savings, are relevant to the stringent mitigation scenarios (van der Zwaan et al., 2013). Indeed, many scenarios show no dominant transport fuel source in 2100, with the median values for electricity and hydrogen sitting between a 22–25 % share of final energy, even for scenarios consistent with limiting concentrations to 430–530 ppm CO_2eq in 2100 (Figure 8.12).

Both the integrated and sectoral model literature present energy efficiency measures as having the greatest promise and playing the largest role for emission reductions in the short term (Skinner et al., 2010; Harvey, 2012; IEA, 2009; McKinnon and Piecyk, 2009; Sorrell et al., 2012). Since models typically assume limited cost reduction impacts, they include slow transitions for new transport technologies to reach large cumulative market shares. For example, a range of both sectoral and integrated studies note that it will take over 15–20 years for either BEVs or FCVs to become competitive with ICE vehicles (Baptista et al., 2010; Eppstein et al., 2011; IEA, 2011c; Girod et al., 2012; Girod et al., 2013; Bosetti and Longden, 2013; van der Zwaan et al., 2013). Since integrated models do not contain a detailed representation of infrastructural changes, their results can be interpreted as a conservative estimate of possible changes to vehicles, fuels, and modal choices (Pietzcker et al., 2013).

The sectoral literature presents a more positive view of transformational opportunities than do the integrated models (IEA, 2008, 2012b; DOE/EIA, 2010; Kahn Ribeiro et al., 2012). Sectoral studies suggest that up to 20 % of travel demand could be reduced by avoided journeys or shifts to low-carbon modes (McCollum and Yang, 2009; Harvey, 2012; IEA, 2012d; Kahn Ribeiro et al., 2012; Anable et al., 2012;

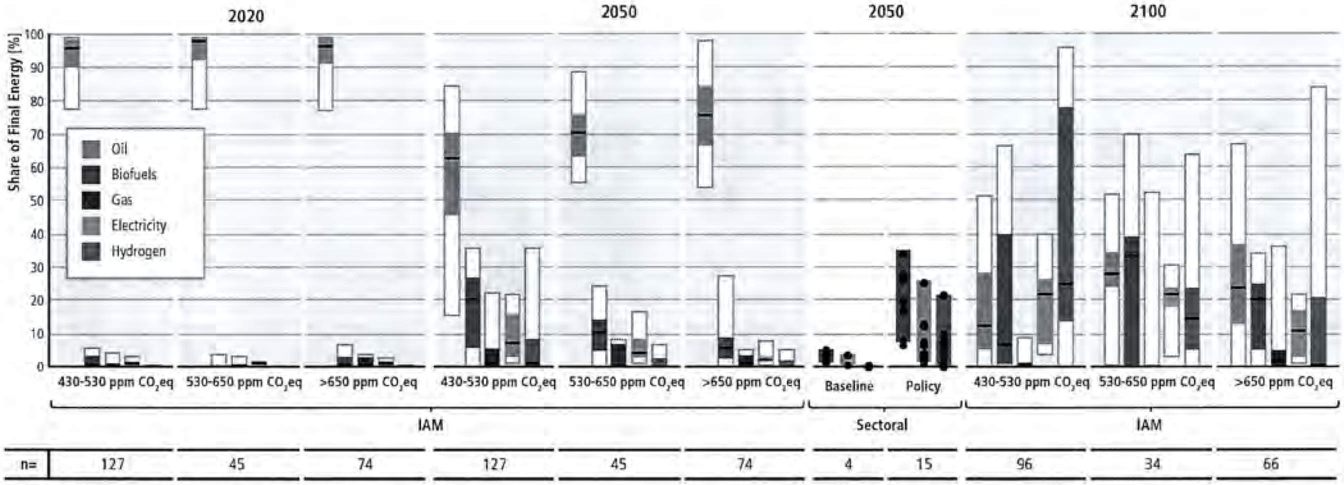

Figure 8.12 | Global shares of final fuel energy in the transport sector in 2020, 2050, and 2100 based on integrated models grouped by CO_2eq concentration levels by 2100 and compared with sectoral models (grouped by baseline and policies) in 2050. Box plots show minimum/maximum, 25th/75th percentile and median. Source: *Integrated models*—WG III AR5 Scenario Database (Annex II.10). Sectoral models—IEA, 2012; IEA, 2011b; IEA, 2008; WEC, 2011a; EIA, 2011 and IEEJ, 2011.

Note: Interpretation is similar to that for Figs. 8.9 and 8.10, except that the boxes between the 75th and 25th percentiles for integrated model results have different colours to highlight the fuel type instead of GHG concentration categories. The specific observations from sectoral studies are shown as black dots

Box 8.1 | Transport and sustainable development in developing countries

Passenger and freight mobility are projected to double in developing countries by 2050 (IEA, 2012e). This increase will improve access to markets, jobs, education, healthcare and other services by providing opportunities to reduce poverty and increase equity (Africa Union, 2009; Vasconcellos, 2011; United Nations Human Settlements Programme, 2012). Well-designed and well-managed transport infrastructure can also be vital for supporting trade and competitiveness (United Nations Human Settlements Programme, 2012). Driven by urbanization, a rapid transition from slow non-motorized transport modes to faster modes using 2- or 3- wheelers, LDVs, buses, and light rail is expected to continue (Schäfer et al., 2009; Kumar, 2011). In rural areas of Africa and South Asia, the development of all-season, high-quality roads is becoming a high priority (Africa Union, 2009; Arndt et al., 2012). In many megacities, slum area development in peri-urban fringes confines the urban poor to a choice between low paying jobs near home or long commuting times for marginally higher wages (Burdett and Sudjic, 2010). The poor have limited options to change living locations and can afford few motorized trips, so they predominantly walk, which disproportionally burdens women and children (Anand and Tiwari, 2006; Pendakur, 2011). The urban poor in OECD cities have similar issues (Glaeser, 2011). Reducing vulnerability to climate change requires integrating the mobility needs of the poor into planning that can help realize economic and social development objectives (Amekudzi et al., 2011; Bowen et al., 2012).

Total transport emissions from non-OECD countries will likely surpass OECD emissions by 2050 due to motorization, increasing population and higher travel demand (Figure 8.10). However, estimated average personal travel per capita in non-OECD countries at will remain below the average in OECD countries. With countries facing limits to transport infrastructure investment (Arndt et al., 2012), the rapid mobility trends represents a major challenge in terms of traffic congestion, energy demand, and related GHG emissions (IEA, 2012a). Failure to manage the growth of motorized mobility in the near term will inevitably lead to higher environmental cost and greater difficulty to control emissions in the long term (Schäfer et al., 2009; Pietzcker et al., 2013).

A high modal share of public transport use characterizes developing cities (Estache and GóMez-Lobo, 2005) and this prevalence is expected to continue (Deng and Nelson, 2011; Cuenot et al., 2012). However, deficient infrastructure and inadequate services leads to the overloading of para-transit vans, minibuses, jeeps and shared taxis and the use of informal transport services (Cervero and Golub, 2011). By combining technologies, providing new social arrangements, and incorporating a long-term sustainability and climate perspective to investment decisions, these services can be recast and maintained as mobility resources since they service the poor living in inaccessible areas at affordable prices (Figueroa et al., 2013). A central strategy that can have multiple health, climate, environmental, and social benefits is to invest in the integration of infrastructure systems that connect safe routes for walking and cycling with local public transport, thus giving it priority over infrastructure for LDVs that serve only a small share of the population (Woodcock et al., 2009; Tiwari and Jain, 2012). Opportunities for strategic sustainable urban transport development planning exist that can be critical to develop medium sized cities where population increases are expected to be large (Wittneben et al., 2009; ADB, 2012b; Grubler et al., 2012). Vision, leadership, and a coherent programme for action, adaptation, and consolidation of key institutions that can harness the energy and engagement of all stakeholders in a city will be needed to achieve these goals (Dotson, 2011). Today, more than 150 cities worldwide have implemented bus rapid transit (BRT) systems. Innovative features such as electric transit buses (Gong et al., 2012) and the ambitious high-speed rail expansion in China provide evidence of a fast process of planning and policy implementation.

Huo and Wang, 2012). They also estimate that urban form and infrastructure changes can play decisive roles in mitigation, particularly in urban areas where 70 % of the world's population is projected to live in 2050 (Chapter 8.4 and 12.4), although the estimated magnitude varies between 5 % and 30 % (Ewing, 2007; Creutzig and He, 2009; Echenique et al., 2012). Altogether, for urban transport, 20–50 % reduction in GHG emissions is possible between 2010 and 2050 compared to baseline urban development (Ewing, 2007; Eliasson, 2008; Creutzig and He, 2009; Lefèvre, 2009; Woodcock et al., 2009; Ewing and Cervero, 2010; Marshall, 2011; Echenique et al., 2012; Viguié and Hallegatte, 2012; Salon et al., 2012; Creutzig et al., 2012a). Since the lead time for infrastructure development is considerable (Short and Kopp, 2005), such changes can only be made on decadal time scales. Conversely, some developing countries with fast growing economies have shown that rapid transformative processes in spatial development and public transport infrastructure are possible. Further advances may be gaining momentum with a number of significant initiatives for reallocating public funding to sustainable and climate-friendly transport (Bongardt et al., 2011; Wittneben et al., 2009; ADB, 2012; Newman and Matan, 2013).

8.9.2 Sustainable development

Within all scenarios, the future contribution of emission reductions from developing countries carries especially large uncertainties. The accelerated pace with which both urbanization and motorization are proceeding in many non-OECD countries emphasizes serious constraints and potentially damaging developments. These include road and public transport systems that are in dire condition; limited technical and financial resources; the absence of infrastructure governance; poor legal frameworks; and rights to innovate that are needed to act effectively and improve capacity competences (Kamal-Chaoui and Plouin, 2012; Lefèvre, 2012). The outcome is a widening gap between the growth of detrimental impacts of motorization and effective action (Kane, 2010; Li, 2011; Vasconcellos, 2011). A highly complex and changing context with limited data and information further compromise transport sustainability and mitigation in non-OECD countries (Dimitriou, 2006; Kane, 2010; Figueroa et al., 2013). The relative marginal socio-economic costs and benefits of various alternatives can be context sensitive with respect to sustainable development (Amekudzi, 2011). Developing the analytical and data capacity for multi-objective evaluation and priority setting is an important part of the process of cultivating sustainability and mitigation thinking and culture in the long-term.

Potentials for controlling emissions while improving accessibility and achieving functional mobility levels in the urban areas of rapidly growing developing countries can be improved with attention to the manner in which the mobility of the masses progresses in their transition from slower (walking/cycling) to faster motorized modes (Kahn Ribeiro et al., 2012). A major shift towards the use of mass public transport guided by sustainable transport principles, including the maintenance of adequate services and safe infrastructure for non-motorized transport, presents the greatest mitigation potential (Bongardt et al., 2011; La Branche, 2011). Supporting non-motorized travel can often provide access and also support development more effectively, more equitably, and with fewer adverse side-effects, than if providing for motorized travel (Woodcock et al., 2007). Transport can be an agent of sustained urban development that prioritizes goals for equity and emphasizes accessibility, traffic safety, and time savings for the poor with minimal detriment to the environment and human health, all while reducing emissions (Amekudzi et al., 2011; Li, 2011; Kane, 2010). The choice among alternative mitigation measures in the transport sector can be supported by growing evidence on a large number of co-benefits, while some adverse side effects exist that need to be addressed or minimized (see Section 8.7) (Figueroa and Kahn Ribeiro, 2013; Creutzig and He, 2009; Creutzig et al., 2012a, b; Zusman et al., 2012).

8.10 Sectoral policies

Aggressive policy intervention is needed to significantly reduce fuel carbon intensity and energy intensity of modes, encourage travel by the most efficient modes, and cut activity growth where possible and reasonable (see Sections 8.3 and 8.9). In this section, for each major transport mode, policies and strategies are briefly discussed by policy type as regulatory or market-based, or to a lesser extent as informational, voluntary, or government-provided. A full evaluation of policies across all sectors is presented in Chapters 14 and 15. Policies to support sustainable transport can simultaneously provide co-benefits (Table 8.4) such as improving local transport services and enhancing the quality of environment and urban living, while boosting both climate change mitigation and energy security (ECMT, 2004; WBCSD, 2004, 2007; World Bank, 2006; Banister, 2008; IEA, 2009; Bongardt et al., 2011; Ramani et al., 2011; Kahn Ribeiro et al., 2012). The type of policies, their timing, and chance of successful implementation are context dependent (Santos et al., 2010). Diverse attempts have been made by transport agencies in OECD countries to define and measure policy performance (OECD, 2000; CST, 2002; Banister, 2008; Ramani et al., 2011). The mobility needs in non-OECD countries highlight the importance of placing their climate-related transport policies in the context of goals for broader sustainable urban development goals (see Section 8.9; Kahn Ribeiro et al., 2007; Bongardt et al., 2011).

Generally speaking, market-based instruments, such as carbon cap and trade, are effective at incentivizing all mitigation options simultaneously (Flachsland et al., 2011). However, vehicle and fuel suppliers as well as end-users, tend to react weakly to fuel price signals, such as fuel carbon taxes, especially for passenger travel (Creutizig et al., 2011; Yeh and McCollum, 2011). Market policies are economically more efficient at reducing emissions than fuel carbon intensity standards (Holland et al., 2009; Sperling and Yeh, 2010; Chen and Khanna, 2012; Holland, 2012). However, financial instruments, such as carbon taxes, must be relatively large to achieve reductions equivalent to those possible with regulatory instruments. As a result, to gain large emissions reductions a suite of policy instruments will be needed (NRC, 2011c; Sperling and Nichols, 2012), including voluntary schemes, which have been successful in some circumstances, such as for the Japanese airline industry (Yamaguchi, 2010).

8.10.1 Road transport

A wide array of policies and strategies has been employed in different circumstances to restrain private LDV use, promote mass transit modes, manage traffic congestion and promote new fuels in order to reduce fossil fuel use, air pollution, and GHG emissions. These policies and strategies overlap considerably, often synergistically.

The magnitude of urban growth and population redistribution from rural to urban areas in emerging and developing countries is expected to continue (see Sections 8.2 and 12.2). This implies a large increase in demand for motorized transport especially in medium-size cities (Grubler et al., 2012). In regions and countries presently with low levels of LDV ownership, opportunities exist for local and national governments to manage future rising road vehicle demand in ways that support economic growth, provide broad social benefits (Wright and Fulton, 2005; IEA, 2009; Kato et al., 2005) and keep GHG emissions in bounds. Local history and social culture can help shape the specific problem, together with equity implications and policy aspirations that ultimately determine what will become acceptable solutions (Vasconcellos, 2001; Dimitriou, 2006; Kane, 2010; Li, 2011; Verma et al., 2011).

Even if non-OECD countries pursue strategies and policies that encourage LDV use for a variety of economic, social, and environmental motivations, per capita LDV travel in 2050 could remain far below OECD countries. However, in many OECD countries, passenger LDV travel demand per capita appears to have begun to flatten, partly driven by increasing levels of saturation and polices to manage increased road transport demand (Section 8.2.1; Millard-Ball and Schipper, 2011; Schipper, 2011; Goodwin, 2012; IEA, 2012c; Meyer et al., 2012). Even if this OECD trend of slowing growth in LDV travel continues or even eventually heads downwards, it is unlikely to offset projected growth in non-OECD LDV travel or emissions because those populations and economies are likely to continue to grow rapidly along with LDV ownership. Only with very aggressive policies in both OECD and non-OECD countries would total global LDV use stabilize in 2050. This is illustrated in a 2 °C LDV transport scenario generated by Fulton et al. (2013), using mainly IEA (2012c) data. In that policy scenario, LDV travel in OECD countries reaches a peak of around 7500 vehicle km/capita in 2035 then drops by about 20 % by 2050. By comparison, per capita LDV travel in non-OECD countries roughly quadruples from an average of around 500 vehicle km/capita in 2012 to about 2000 vehicle km/capita in 2050, remaining well below the OECD average.

Many countries have significant motor fuel taxes that, typically, have changed little in recent years. This indicates that such a market instrument is not a policy tool being used predominantly to reduce GHG emissions. The typical approach increasingly being used is a suite of regulatory and other complementary policies with separate instruments for vehicles and for fuels. The challenge is to make them consistent and coherent. For instance, the fuel efficiency and GHG emission standards for vehicles in Europe and the United States give multiple credits to plug-in electric vehicles (PEVs) and fuel cell vehicles (FCVs). Zero upstream emissions are assigned, although this is technically incorrect but designed to be an implicit subsidy (Lutsey and Sperling, 2012).

Fuel choice and carbon intensity[10]. Flexible fuel standards that combine regulatory and market features include the Californian low-carbon fuel standard (LCFS) (Sperling and Nichols, 2012) and the European Union fuel quality directive (FQD). Fuel carbon intensity reduction targets for 2020 (10 % for California and 6 % for EU) are expected to be met by increasing use of low-carbon biofuels, hydrogen, and electricity. They are the first major policies in the world premised on the measurement of lifecycle GHG intensities (Yeh and Sperling, 2010; Creutzig et al., 2011), although implementation of lifecycle analyses can be challenging and sometimes misleading since it is difficult to design implementable rules that fully include upstream emissions (Lutsey and Sperling, 2012); emissions resulting from induced market effects; and emissions associated with infrastructure, the manufacturing of vehicles, and the processing and distribution of fuels (for LCA see Annex II.6.3 Kendall and Price, 2012).

Biofuel policies have become increasingly controversial as more scrutiny is applied to the environmental and social equity impacts (Section 11.13). In 2007, the European Union and the United States adopted aggressive biofuel policies (Yeh and Sperling, 2013). The effectiveness of these policies remains uncertain, but follow-up policies such as California's LCFS and EU's FQD provide broader, more durable policy frameworks that harness market forces (allowing trading of credits), and provide flexibility to industry in determining how best to reduce fuel carbon intensity. Other related biofuel policies include subsidies (IEA, 2011d) and mandatory targets (REN21, 2012).

Vehicle energy intensity. The element of transport that shows the greatest promise of being on a trajectory to achieve large reductions in GHG emissions by 2050 is reducing the energy and fuel carbon intensities of LDVs. Policies are being put in place to achieve dramatic improvements in vehicle efficiency, stimulating automotive companies to make major investments. Many countries have now adopted aggressive targets and standards (Figure 8.13), with some standards criticized

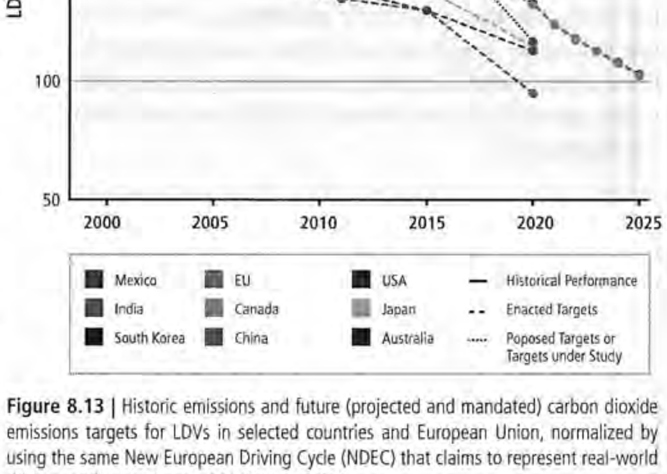

Figure 8.13 | Historic emissions and future (projected and mandated) carbon dioxide emissions targets for LDVs in selected countries and European Union, normalized by using the same New European Driving Cycle (NDEC) that claims to represent real-world driving conditions. Source: ICCT (2007, 2013)

Notes: (1) China's target reflects gasoline LDVs only and may become higher if new energy vehicles are considered. (2) Gasoline in Brazil contains 22 % ethanol but data here are converted to 100 % gasoline equivalent.

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[10] The following four sub-sections group policies along the lines of the decomposition as outlined in 8.1 and Figure 8.2

for not representing real-world conditions (Mock et al., 2012). Most are developed countries, but some emerging economies, including China and India, are also adopting increasingly aggressive standards (Wang et al., 2010).

Regulatory standards focused on fuel consumption and GHG emissions vary in their design and stringency. Some strongly stimulate reductions in vehicle size (as in Europe) and others provide strong incentives to reduce vehicle weight (as in the United States) (CCC, 2011). All have different reduction targets. As of April 2010, 17 European countries had implemented taxes on LDVs wholly or partially related to CO_2 emissions. Regulatory standards require strong market instruments and align market signals with regulations as they become tighter over time. Examples are fuel and vehicle purchase taxes and circulation taxes that can limit rebound effects. Several European countries have established revenue-neutral feebate schemes (a combination of *rebates* awarded to purchasers of low carbon emission vehicles and *fees* charged to purchasers of less efficient vehicles) (Greene and Plotkin, 2011). Annual registration fees can have similar effects if linked directly with carbon emissions or with related vehicle attributes such as engine displacement, engine power, or vehicle weight (CARB, 2012). One concern with market-based policies is their differential impact across population groups such as farmers needing robust vehicles to traverse rugged terrain and poor quality roads. Equity adjustments can be made so that farmers and large families are not penalized for having to buy a large car or van (Greene and Plotkin, 2011).

Standards are likely to spur major changes in vehicle technology, but in isolation are unlikely to motivate significant shifts away from petroleum-fuelled ICE vehicles. In the United States, a strong tightening of standards through to 2025 is estimated to trigger only a 1 % market share for PEVs if only economics is considered (EPA, 2011).

A more explicit regulatory instrument to promote EVs and other new, potentially very-low carbon propulsion technologies is a zero emission vehicle mandate, as originally adopted by California in 1990 to improve local air quality, and which now covers almost 30 % of the United States market. This policy, now premised on reducing GHGs, requires about 15 % of new vehicles in 2025 to be a mix of PEVs and FCVs (CARB, 2012).

There are large potential efficiency improvements possible for medium and heavy-duty vehicles (HDVs) (see Section 8.3.1.2), but policies to pursue these opportunities have lagged those for LDVs. Truck types, loads, applications, and driving cycles are much more varied than for LDVs and engines are matched with very different designs and loads, thereby complicating policy-making. However, China implemented fuel consumption limits for HDVs in July 2012 (MIIT, 2011); in 2005 Japan set modest fuel efficiency standards to be met by 2015 (Atabani et al., 2011); California, in 2011, required compulsory retrofits to reduce aerodynamic drag and rolling resistance (Atabani et al., 2011); the United States adopted standards for new HDVs and buses manufactured from 2014 to 2018 (Greene and Plotkin, 2011); and the EU intends to pursue similar actions including performance standards and fuel efficiency labelling by 2014 (Kojima and Ryan, 2010). Aggressive air pollution standards since the 1990s for NO_x and particulate matter emissions from HDVs in many OECD countries have resulted in a fuel consumption penalty in the past of 7 % to 10 % (IEA, 2009; Tourlonias and Koltsakis, 2011). However, emission technology improvements and reductions in black carbon emissions, which strongly impact climate change (see Section 8.2.2.1), will offset some of the negative effect of this increased fuel consumption.

Activity reduction. A vast and diverse mix of policies is used to restrain and reduce the use of LDVs, primarily by focusing on land use patterns, public transport options, and pricing. Other policy strategies to reduce activity include improving traffic management (Barth and Boriboonsomsin, 2008), better truck routing systems (Suzuki, 2011), and smart real-time information to reduce time searching for a parking space. Greater support for innovative services using information and communication technologies, such as dynamic ride sharing and demand-responsive para-transit services (see Section 8.4), creates still further opportunities to shift toward more energy efficient modes of travel.

Policies can be effective at reducing dependence on LDVs as shown by comparing Shanghai with Beijing, which has three times as many LDVs even though the two cities have similar levels of affluence, the same culture, and are of a similar population (Hao et al., 2011). Shanghai limited the ownership of LDVs by establishing an expensive license auction, built fewer new roads, and invested more in public transport, whereas Beijing built an extensive network of high capacity expressways and did little to restrain car ownership or use until recently. The Beijing city administration has curtailed vehicle use by forbidding cars to be used one day per week since 2008, and sharply limited the number of new license plates issued each year since 2011 (Santos et al., 2010) Hao et al., 2011). The main aims to reduce air pollution, traffic congestion, and costs of road infrastructure exemplify how policies to reduce vehicle use are generally, but not always, premised on non-GHG co-benefits. European cities have long pursued demand reduction strategies, with extensive public transport supply, strict growth controls, and more recent innovations such as bicycle sharing. California seeks to create more liveable communities by adopting incentives, policies, and rules to reduce vehicle use, land use sprawl, and GHG emissions from passenger travel. The California law calls for 6–8 % reduction in GHG emissions from passenger travel per capita (excluding changes in fuel carbon intensity and vehicle energy intensity) in major cities by 2020, and 13–16 % per capita by 2035 (Sperling and Nichols, 2012).

The overall effectiveness of initiatives to reduce or restrain road vehicle use varies dramatically depending on local commitment and local circumstances, and the ability to adopt synergistic policies and practices by combining pricing, land use management, and public transport measures. A broad mix of policies successfully used to reduce vehicle use in OECD countries, and to restrain growth in emerging economies, includes pricing to internalize energy, environmental, and health costs; strengthening land use management; and providing more and better public transport.

Policies to reduce LDV activity can be national, but mostly they are local, with the details varying from one local administration to another.

Some policies are intrinsically more effective than others. For instance, fuel taxes will reduce travel demand but drivers are known to be relatively inelastic in their response (Hughes et al., 2006; Small and van Dender, 2007). However, drivers are more elastic when price increases are planned and certain (Sterner, 2007). Pricing instruments such as congestion charges, vehicle registration fees, road tolls and parking management can reduce LDV travel by inducing trip chaining, modal shifts, and reduced use of cars (Litman, 2006). Policies and practices of cities in developing countries can be influenced by lending practices of development banks, such as the Rio+20 commitment to spend approximately 170 billion USD_{2010} on more sustainable transport projects, with a focus on Asia (ADB, 2012c).

System efficiency. Improvements have been far greater in freight transport and aviation than for surface passenger transport (rail and road). Freight transport has seen considerable innovation in containerization and intermodal connections, as has aviation, though the effects on GHG emissions are uncertain (and could be negative because of just-in-time inventory management practices). For surface passenger travel, efforts to improve system efficiency and inter-modality are hindered by conflicting and overlapping jurisdictions of many public and private sector entities and tensions between fiscal, safety, and equity goals. Greater investment in roads than in public transport occurred in most cities of developed countries through the second half of the 20th century (Owens, 1995; Goodwin, 1999). The 21st century, though, has seen increasing government investment in bus rapid transit and rail transit in OECD countries (Yan and Crookes, 2010; Tennøy, 2010) along with increasing support for bicycle use.

Since the 1960s, many cities have instigated supportive policies and infrastructure that have resulted in a stable growth in cycling (Servaas, 2000; Hook, 2003; TFL, 2007; NYC, 2012). Several European cities have had high cycle transport shares for many years, but now even in London, UK, with efficient public transport systems, the 2 % cycle share of travel modes is targeted to increase to 5 % of journeys in 2026 as a result of a range of new policies (TFL, 2010). However, in less developed cities such as Surabaya, Indonesia, 10 % of total trips between 1–3 km are already by cycling (including rickshaws) in spite of unsupportive infrastructure and without policies since there are few affordable alternatives (Hook, 2003). Where cycle lanes have been improved, as in Delhi, greater uptake of cycling is evident (Tiwari and Jain, 2012).

8.10.2 Rail transport

Rail transport serves 28 billion passengers globally, carrying them around 2500 billion p-km/yr[11]. Rail also carries 11.4 billion tonne of freight (8845 billion t-km/yr) (Johansson et al., 2012). Policies to further improve system efficiency may improve competitiveness and opportunities for modal shift to rail (Johansson et al., 2012). Specific energy and carbon intensities of rail transport are relatively small compared to some other modes (see Section 8.3). System efficiency can also be assisted through train driver education and training policies (Camagni et al., 2002).

Fuel intensity. Roughly one third of all rail transport is driven by diesel and two-thirds by electricity (Johansson et al., 2012). Policies to reduce fuel carbon intensity are therefore linked to a large extent to those for decarbonizing electricity production (Chapter 7; DLR, 2012). For example, Sweden and Switzerland are running their rail systems using very low carbon electricity (Gössling, 2011).

Energy intensity. Driven largely by corporate strategies, the energy intensity of rail transport has been reduced by more than 60 % between 1980 and 2001 in the United States (Sagevik, 2006). Overall reduction opportunities of 45–50 % are possible for passenger transport in the EU and 40–50 % for freight (Andersson et al., 2011). Recent national policies in the United Kingdom and Germany appear to have resulted in 73 % rail freight growth over the period 1995–2007, partly shifted from road freight.

System efficiency. China, Europe, Japan, Russia, United States and several Middle-eastern and Northern African countries continue (or are planning) to invest in high-speed rail (HSR) (CRC, 2008). It is envisaged that the worldwide track length of about 15,000 km in 2012 will nearly triple by 2025 due to government supporting policies, allowing HSR to better compete with medium haul aviation (UIC, 2012).

8.10.3 Waterborne transport

Although waterborne transport is comparatively efficient in terms of gCO_2/t-km compared to other freight transport modes (see Section 8.6), the International Maritime Organization (IMO) has adopted mandatory measures to reduce GHG emissions from international shipping (IMO, 2011). This is the first mandatory GHG reduction regime for an international industry sector and for the standard to be adopted by all countries is a model for future international climate change co-operation for other sectors (Yamaguchi, 2012). Public policies on emissions from inland waterways are nationally or regionally based and currently focus more on the reduction of NO_x and particulate matter than on CO_2. However, policy measures are being considered to reduce the carbon intensity of this mode including incentives to promote 'smart steaming', upgrade to new, larger vessels, and switch to alternative fuels, mainly LNG (Panteia, 2013). Few if any, policies support the use of biofuels, natural gas or hydrogen for small waterborne craft around coasts or inland waterways and little effort has been made to assess the financial implications of market (and other) policies on developing countries who tend to import and export low value-to-weight products, such as food and extractible resources (Faber et al., 2012).

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[11] By way of comparison, aviation moves 2.1 billion passengers globally (some 3900 billion p-km/yr).

Energy intensity. IMO's Energy Efficiency Design Index (EEDI) is to be phased in between 2013 and 2025. It aims to improve the energy efficiency of certain categories of new ships and sets technical standards (IMO, 2011). However, the EEDI may not meet the target if shipping demand increases faster than fuel carbon and energy intensities improve. The voluntary Ship Energy Efficiency Management Plan (SEEMP) was implemented in 2013 (IMO, 2011). For different ship types and sizes it provides a minimum energy efficiency level. As much as 70 % reduction of emissions from new ships is anticipated with the aim to achieve approximately 25–30 % reductions overall by 2030 compared with business-as-usual (IISD, 2011). It is estimated that, in combination, EEDI requirements and SEEMP will cut CO_2 emissions from shipping by 13 % by 2020 and 23 % by 2030 compared to a 'no policy' baseline (Lloyds Register and DNV, 2011).

8.10.4 Aviation

After the Kyoto Protocol directed parties in Annex I to pursue international aviation GHG emission limitation/reduction working through the International Civil Aviation Organization (ICAO) (Petersen, 2008), member states are working together with the industry towards voluntarily improving technologies, increasing the efficient use of airport infrastructure and aircraft, and adopting appropriate economic measures (ICAO, 2007b; ICAO, 2010a). In 2010, ICAO adopted global aspirational goals for the international aviation sector to improve fuel efficiency by an average of 2 % per annum until 2050 and to keep its global net carbon emissions from 2020 at the same level (ICAO, 2010b). These goals exceed the assumptions made in many scenarios (Mayor and Tol, 2010).

Policy options in place or under consideration include regulatory instruments (fuel efficiency and emission standards at aircraft or system levels); market-based approaches (emission trading under caps, fuel taxes, emission taxes, subsidies for fuel efficient technologies); and voluntary measures including emission offsets (Daley and Preston, 2009). Environmental capacity constraints on airports also exist and may change both overall volumes of air transport and modal choice (Upham et al., 2004; Evans, 2010). National policies affect mainly domestic aviation, which covers about 30–35 % of total air transport (IATA, 2009; Lee et al., 2009; Wood et al., 2010). A nationwide cap-and-trade policy could have the unintended consequence of slowing aircraft fleet turnover and, through diverted revenue, of delaying technological upgrades, which would slow GHG reductions, though to what degree is uncertain (Winchester et al., 2013). In the UK, an industry group including airport companies, aircraft manufacturers and airlines has developed a strategy for reducing GHG emissions across the industry (Sustainable Aviation, 2012).

The EU is currently responsible for 35 % of global aviation emissions. The inclusion of air transport in the EU emission trading scheme (ETS) is the only binding policy to attempt to mitigate emissions in this sector (Anger, 2010; Petersen, 2008; Preston et al., 2012). The applicability of ETS policy to non-European routes (for flights to and from destinations outside the EU) (Malina et al., 2012) has been delayed for one year, but the directive continues to apply to flights between destinations in the EU following a proposal by the European Commission in November 2012 in anticipation of new ICAO initiatives towards a global market-based mechanism for all aviation emissions (ICAO, 2012).

Taxing fuels, tickets, or emissions may reduce air transport volume with elasticities varying between −0.3 to −1.1 at national and international levels, but with strong regional differences (Europe has 40 % stronger elasticities than most other world regions, possibly because of more railway options). Airport congestion adds considerable emissions (Simaiakis and Balakrishnan, 2010) and also tends to moderate air transport demand growth to give a net reduction of emissions at network level (Evans and Schäfer, 2011).

Fuel carbon intensity. Policies do not yet exist to introduce low-carbon biofuels. However, the projected GHG emission reductions from the possible future use of biofuels, as assumed by the aviation industry, vary between 19 % of its adopted total emission reduction goal (Sustainable Aviation, 2008) to over 50 % (IATA, 2009),depending on the assumptions made for the other reduction options that include energy efficiency, improved operation and trading emission permits. Sustainable production issues also apply (see Section 8.3.3).

Energy intensity. The energy efficiency of aircraft has improved historically without any policies in force, but with the rate of fuel consumption reducing over time from an initial 3–6 % in the 1950s to between 1 % and 2 % per year at the beginning of the 21st century (Pulles et al., 2002; Fulton and Eads, 2004; Bows et al., 2005; Peeters and Middel, 2007; Peeters et al., 2009). This slower rate of fuel reduction is possibly due to increasing lead-times required to develop, certify, and introduce new technology (Kivits et al., 2010).

System efficiency. The interconnectedness of aviation services can be a complicating factor in adopting policies, but also lends itself to global agreements. For example, regional and national air traffic controllers have the ability to influence operational efficiencies. The use of market policies to reduce GHG emissions is compelling because it introduces a price signal that influences mitigation actions across the entire system. But like other aspects of the passenger transport system, a large price signal is needed with aviation fuels to gain significant reductions in energy use and emissions (Tol, 2007; Peeters and Dubois, 2010; OECD and UNEP, 2011). Complementary policies to induce system efficiencies include measures to divert tourists to more efficient modes such as high-speed rail. However, since short- and medium-haul aircraft now have similar energy efficiencies per passenger km compared to LDVs (Figure 8.6), encouraging people to take shorter journeys (hence by road instead of by air), thereby reducing tourism total travel, has become more important (Peeters and Dubois, 2010). No country has adopted a low-carbon tourism strategy (OECD and UNEP, 2011).

8.10.5 Infrastructure and urban planning

Urban form has a direct effect on transport activity (see Section 12.4). As a consequence, infrastructure policies and urban planning can provide major contributions to mitigation (see Section 12.5). A modal shift from LDVs to other surface transport modes could be partly incentivized by policy measures that impose physical restrictions as well as pricing regimes. For example, LDV parking management is a simple form of cost effective, pricing instrument (Barter et al., 2003; Litman, 2006). Dedicated bus lanes, possibly in combination with a vehicle access charge for LDVs, can be strong instruments to achieving rapid shifts to public transport (Creutzig and He, 2009).

Policies that support the integration of moderate to high density urban property development with transit-oriented development strategies that mix residential, employment, and shopping facilities can encourage pedestrians and cyclists, thereby giving the dual benefits of reducing car dependence and preventing urban sprawl (Newman and Kenworthy, 1996; Cervero, 2004; Olaru et al., 2011). GHG emissions savings (Trubka et al., 2010a; Trubka et al., 2010b) could result in co-benefits of health, productivity, and social opportunity (Trubka et al., 2010c; Ewing and Cervero, 2010; Höjer et al., 2011) if LDV trips could be reduced using polycentric city design and comprehensive smart-growth policies (Dierkers et al., 2008). Policies to support the building of more roads, airports, and other infrastructure can help relieve congestion in the short term, but can also induce travel demand (Duranton and Turner, 2011) and create GHG emissions from construction (Chester and Horvath, 2009).

8.11 Gaps in knowledge and data

The following gaps made assessing the mitigation potential of the transport sector challenging.

Gaps in the basic statistics are still evident on the costs and energy consumption of freight transport, especially in developing countries.

- Data and understanding relating to freight logistical systems and their economic implications are poor, as are the future effects on world trade of decarbonization and climate change impacts. Hence, it is difficult to design new low-carbon freight policies.
- Future technological developments and costs of batteries, fuel cells, and vehicle designs are uncertain.
- The infrastructure requirement for new low-carbon transport fuels is poorly understood.
- Cost of components for novel vehicle powertrains cannot be determined robustly since rates of learning, cost decreases, and associated impacts are unknown.
- Assessments of mitigating transport GHG emissions, the global potential, and costs involved are inconsistent.
- Prices of crude oil products fluctuate widely as do those for alternative transport fuels, leading to large variations in scenario modelling assumptions.
- A better knowledge of consumer travel behaviour is needed, particularly for aviation.
- Limited understanding exists of how and when people will choose to buy and use new types of low-carbon vehicles or mobility services (such as demand responsive transit or car-share).
- There are few insights of behavioural economics to predict mobility systematically and whether producers will incorporate low-carbon technologies that may not maximize profit.
- How travellers will respond to combinations of low-carbon strategies (mixes of land use, transit, vehicle options) is especially important for fast-growing, developing countries where alternative modes to the car-centric development path could be deployed, is unknown.
- Understanding how low-carbon transport and energy technologies will evolve (via experience curves and innovation processes) is not well developed. Most vehicles rely on stored energy, so there is a need to better understand the cost and energy density of non-hydrocarbon energy storage mediums, such as batteries, super-capacitors and pressure vessels.
- Decoupling of transport GHG from economic growth needs further elaboration, especially the policy frameworks that can enable this decoupling to accelerate in both OECD and non-OECD nations.
- The rate of social acceptance of innovative concepts such as LDV road convoys, induction charging of electric vehicles, and driverless cars (all currently being demonstrated) is difficult to predict, as is the required level of related infrastructure investments. Recent rapid developments in metro systems in several cities illustrate how quickly new transport systems can be implemented when the demand, policies, and investments all come together and public support is strong.

8.12 Frequently Asked Questions

FAQ 8.1 How much does the transport sector contribute to GHG emissions and how is this changing?

The transport sector is a key enabler of economic activity and social connectivity. It supports national and international trade and a large global industry has evolved around it. Its greenhouse gas (GHG) emissions are driven by the ever-increasing demand for mobility and movement of goods. Together, the road, aviation, waterborne, and rail transport sub-sectors currently produce almost one quarter of total global energy-related CO_2 emissions [Section 8.1]. Emissions have more than doubled since 1970 to reach 7.0 Gt CO_2eq by 2010 with about 80 % of this increase coming from road vehicles. Black carbon and other aerosols, also emitted during combustion of diesel and marine oil fuels, are relatively short-lived radiative forcers compared with carbon dioxide and their reduction is emerging as a key strategy for mitigation [8.2].

Demands for transport of people and goods are expected to continue to increase over the next few decades [8.9]. This will be exacerbated by strong growth of passenger air travel worldwide due to improved affordability; by the projected demand for mobility access in non-OECD countries that are starting from a very low base; and by projected increases in freight movements. A steady increase of income per capita in developing and emerging economies has already led to a recent rapid growth in ownership and use of 2-wheelers, 3-wheelers and light duty vehicles (LDVs), together with the development of new transport infrastructure including roads, rail, airports, and ports.

Reducing transport emissions will be a daunting task given the inevitable increases in demand. Based on continuing current rates of growth for passengers and freight, and if no mitigation options are implemented to overcome the barriers [8.8], the current transport sector's GHG emissions could increase by up to 50 % by 2035 at continued current rates of growth and almost double by 2050 [8.9]. An increase of transport's share of global energy-related CO_2 emissions would likely result. However, in spite of lack of progress in many countries to date, new vehicle and fuel technologies, appropriate infrastructure developments including for non-motorized transport in cities, transport policies, and behavioural changes could begin the transition required [8.3, 8.4, 8.9].

FAQ 8.2 What are the main mitigation options and potentials for reducing GHG emissions?

Decoupling transport from GDP growth is possible but will require the development and deployment of appropriate measures, advanced technologies, and improved infrastructure. The cost-effectiveness of these opportunities may vary by region and over time [8.6]. Delivering mitigation actions in the short-term will avoid future lock-in effects resulting from the slow turnover of stock (particularly aircraft, trains, and ships) and the long-life and sunk costs of infrastructure already in place [8.2, 8.4].

When developing low-carbon transport systems, behavioural change and infrastructure investments are often as important as developing more efficient vehicle technologies and using lower-carbon fuels [8.1, 8.3].

- **Avoidance:** Reducing transport activity can be achieved by avoiding unnecessary journeys, (for example by tele-commuting and internet shopping), and by shortening travel distances such as through the densification and mixed-zoning of cities.
- **Modal choice:** Shifting transport options to more efficient modes is possible, (such as from private cars to public transport, walking, and cycling), and can be encouraged by urban planning and the development of a safe and efficient infrastructure.
- **Energy intensity:** Improving the performance efficiency of aircraft, trains, boats, road vehicles, and engines by manufacturers continues while optimizing operations and logistics (especially for freight movements) can also result in lower fuel demand.
- **Fuel carbon intensity:** Switching to lower carbon fuels and energy carriers is technically feasible, such as by using sustainably produced biofuels or electricity and hydrogen when produced using renewable energy or other low-carbon technologies.

These four categories of transport mitigation options tend to be interactive, and emission reductions are not always cumulative. For example, an eco-driven, hybrid LDV, with four occupants, and fuelled by a low-carbon biofuel would have relatively low emissions per passenger kilometre compared with one driver travelling in a conventional gasoline LDV. But if the LDV became redundant through modal shift to public and non-motorized transport, the overall emission reductions could only be counted once.

Most mitigation options apply to both freight and passenger transport, and many are available for wide deployment in the short term for land, air, and waterborne transport modes, though not equally and at variable costs [8.6]. Bus rapid transit, rail, and waterborne modes tend to be relatively carbon efficient per passenger or tonne kilometre compared with LDV, HDV, or aviation, but, as for all modes, this varies with the vehicle occupancy rates and load factors involved. Modal shift of freight from short- and medium-haul aircraft and road trucks to high-speed rail and coastal shipping often offers large mitigation potential [Table 8.3]. In addition, opportunities exist to reduce the indirect GHG emissions arising during the construction of infrastructure; manufacture of vehicles; and extraction, processing, and delivery of fuels.

The potentials for various mitigation options vary from region to region, being influenced by the stage of economic development, status and age of existing vehicle fleet and infrastructure, and the fuels available in the region. In OECD countries, transport demand reduction may involve changes in lifestyle and the use of new information and communication technologies. In developing and emerging economies, slowing the rate of growth of using conventional transport modes with relatively high-carbon emissions for passenger and freight transport by providing affordable, low-carbon options could play an important role in achieving global mitigation targets. Potential GHG emissions reductions from efficiency improvements on new vehicle designs in 2030 compared with today range from 40–70 % for LDVs, 30–50 % for HDVs, up to 50 % for aircraft, and for new ships when combining technology and operational measures, up to 60 % [Table 8.3].

Policy options to encourage the uptake of such mitigation options include implementing fiscal incentives such as fuel and vehicle taxes, developing standards on vehicle efficiency and emissions, integrating urban and transport planning, and supporting measures for infrastructure investments to encourage modal shift to public transport, walking, and cycling [8.10]. Pricing strategies can reduce travel demands by individuals and businesses, although successful transition of the sector may also require strong education policies that help to create behavioural change and social acceptance. Fuel and vehicle advances in the short to medium term will largely be driven through research investment by the present energy and manufacturing industries that are endeavouring to meet existing policies as well as to increase their market shares. However, in order to improve upon this business-as-usual scenario and significantly reduce GHG emissions across the sector in spite of the rapidly growing demand, more stringent policies will be needed. To achieve an overall transition of the sector will require rapid deployment of new and advanced technology developments, construction of new infrastructure, and the stimulation of acceptable behavioural changes.

FAQ 8.3 Are there any co-benefits associated with mitigation actions?

Climate change mitigation strategies in the transport sector can result in many co-benefits [8.7]. However, realizing these benefits through implementing those strategies depends on the regional context in terms of their economic, social, and political feasibility as well as having access to appropriate and cost-effective advanced technologies. In developing countries where most future urban growth will occur, increasing the uptake, comfort, and safety of mass transit and non-motorized transport modes can help improve mobility. In least developing countries, this may also improve access to markets and therefore assist in fostering economic and social development. The opportunities to shape urban infrastructure and transport systems to gain greater sustainability in the short- to medium-terms are also likely to be higher in developing and emerging economies than in OECD countries where transport systems are largely locked-in [8.4].

A reduction in LDV travel and ownership has been observed in several cities in OECD countries, but demand for motorized road transport, including 2- and 3-wheelers, continues to grow in non-OECD nations where increasing local air pollution often results. Well-designed policy packages can help lever the opportunities for exploiting welfare, safety, and health co-benefits [8.10]. Transport strategies associated with broader policies and programmes can usually target several policy objectives simultaneously. The resulting benefits can include lower travel costs, improved mobility, better community health through reduced local air pollution and physical activities resulting from non-motorized transport, greater energy security, improved safety, and time savings through reduction in traffic congestion.

A number of studies suggest that the direct and indirect benefits of sustainable transport measures often exceed the costs of their implementation [8.6, 8.9]. However, the quantification of co-benefits and the associated welfare effects still need accurate measurement. In all regions, many barriers to mitigation options exist [8.8], but a wide range of opportunities are available to overcome them and give deep carbon reductions at low marginal costs in the medium- to long-term [8.3, 8.4, 8.6, 8.9]. Decarbonizing the transport sector will be challenging for many countries, but by developing well-designed policies that incorporate a mix of infrastructural design and modification, technological advances, and behavioural measures, co-benefits can result and lead to a cost-effective strategy.

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9

Buildings

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Contents

Executive Summary

In 2010 buildings accounted for 32 % of total global final energy use, 19 % of energy-related GHG emissions (including electricity-related), approximately one-third of black carbon emissions, and an eighth to a third of F-gases (*medium evidence, medium agreement*). This energy use and related emissions may double or potentially even triple by mid-century due to several key trends. A very important trend is the increased access for billions of people 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 that is taking place in developing countries represents both a significant risk and opportunity from a mitigation perspective. [Sections 9.1, 9.2]

In contrast to a doubling or tripling, 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 diffused (*robust evidence, high agreement*). The technology solutions to realize this potential exist and are well demonstrated. Recent advances in technology, design practices and know-how, coupled with behavioural changes, can achieve a two to ten-fold reduction in energy requirements of individual new buildings and a two to four-fold reduction for individual existing buildings largely cost-effectively or sometimes even at net negative costs. 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 (*robust evidence, high agreement*). In existing buildings 50–90 % energy savings have been achieved throughout the world through deep retrofits (*medium evidence, high agreement*). Energy efficient appliances, lighting, information communication (ICT), and media technologies can reduce the substantial increases in electricity use that are expected due to the proliferation of equipment types used and their increased ownership and use (*robust evidence, high agreement*). [9.2, 9.3]

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, subsidized 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 stages of the building and appliance lifecycle and use, plus new business and financial models are essential. [9.8, 9.10]

There is a broad portfolio of effective policy instruments available to remove these barriers, some of them being implemented also in developing countries, thus saving emissions at large negative costs (*robust evidence, high agreement*). 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 has started to decrease while accommodating continued economic, and in some 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 programmes and regulation (*medium evidence, medium agreement*). 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 evidence, medium agreement*). 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. [9.10]

Due to the very long lifespans of buildings and retrofits there is a very significant lock-in risk pointing to the urgency of ambitious and immediate measures (*robust evidence, medium agreement*). 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 new building construction and existing building retrofit. As a result, the urgent adoption of state-of-the-art performance standards, in both new and retrofit buildings, avoids locking-in carbon intensive options for several decades. [9.4]

In addition to technologies and architecture, behaviour, lifestyle, and culture have a major effect on buildings' energy use; three- to five-fold difference in energy use has been shown for provision of similar building-related energy service levels (*limited evidence, high agreement*). 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 % of present levels 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 'suf-

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 (PH). 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). Utilization of waste heat (9.4.1.1)	Behavioural change (BC). Lifestyle change (LSC). Smart metering (9.4.1.2)
Potential reductions of energy use/emissions (versus baseline BAU)	Solar electricity generation through buildings' roof-top photo voltaic (PV) installations: energy savings – 15 to – 58 % relative to BAU (Table 9.4)	– 9.5 % to – 68 % energy savings relative to 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 to – 75 %; Ceiling fans: – 50 to – 57 %; Office computers/monitors: – 40 %; Circulation pumps for hydronic heating/cooling: – 40 % (by 2020, EU); Residential water heaters: factor of 4 improvement (Table 9.3); Fuel savings: – 30 to – 60 %; Indoor air pollution levels from advanced biomass stoves (as compared to open fires): – 80 to – 90 % (9.3.8).	– 30 to – 70 % CO2 of BAU. PH & NZEB (new versus conventional building): – 83 % (residential heating energy) and – 50 % (commercial heating & cooling energy); Deep retrofits (DR): – 40 to – 80 % (residential, Europe); IDP: up to – 70 % (final energy by 2050; Table 9.4); Potential global building final energy demand reduction: – 5 % to – 27 % (IAMs), – 14 % to – 75 % (bottom up models) (Fig. 9.21). Energy savings by building type: (i) Detached single-family homes: – 50 – 75 % (total energy use); (ii) Multi-family housing: – 80 to – 90 % (space heating requirements); (iii) Multi-family housing in developing countries: – 30 % (cooling energy use), – 60 % (heating energy); (iv) Commercial buildings: – 25 % to – 50 % (total HVAC), – 30 to – 60 % (lighting retrofits) (9.3.4.1).	– 20 to – 40 % of BAU. LSC about – 40 % electricity use (Table 9.4).
Cost-effectiveness	–	Retrofit of separate measures: CCE: 0.01–0.10 USD_{2010}/kWh (Fig. 9.13). Efficient Appliances: CCE: – 0.09 USD_{2010}/kWh/yr (9.3.4.2)	PH & NZEB (new, EU&USA): CCE: 0.2–0.7 USD_{2010}/kWh (Figure 9.11, 9.12); DR (with energy savings of 60–75 %): CCE: 0.05 – 0.25 USD_{2010}/kWh (Fig. 9.13)	
Co-benefits (CB), adverse side effects (AE)	CB: Energy security; lower need for energy subsidies; health and environmental benefits			
	CB: Employment impact; enhanced asset value of buildings; energy/fuel poverty alleviation. AE: Energy access/fuel poverty	CB: Employment; energy/fuel poverty alleviation; improved productivity/competitiveness; asset value of buildings; improved quality of life. AE: rebound and lock-in effects	CB: Employment impact; improved productivity and competitiveness; enhanced asset values of buildings; improved quality of life. AE: Rebound effect, lower lifecycle energy use of low-energy buildings in comparison to the conventional (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	Carbon 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

ficiency' has also been emerging, going beyond pure 'efficiency'. Reducing energy demand includes rationally meeting floor space needs. [9.3]

Beyond energy cost savings, most mitigation options in this sector have other significant and diverse co-benefits (*robust evidence, high agreement*). 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 evidence, medium agreement*), with the non-monetizable benefits often also being significant (*robust evidence, high agreement*). These benefits offer attractive entry points for action into policy-making, even in countries or jurisdictions where financial resources for mitigation are limited (*robust evidence, high agreement*). These entry points include, but are not limited to, energy security; lower 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 (*medium evidence, high agreement*). However, these are rarely internalized by policies, while a number of tools and approaches are available to quantify and monetize co-benefits that can help this integration (*medium evidence, medium agreement*). [9.7]

In summary, buildings represent a critical piece of a low-carbon future and a global challenge for integration with sustainable development (*robust evidence, high agreement*). Buildings embody the biggest unmet need for basic energy services, especially in developing countries, while much existing energy use in buildings in developed countries is very wasteful and inefficient. Existing and future buildings will determine a large proportion 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 cost-effectively reduce building energy use. Realizing these opportunities requires aggressive and sustained policies and action to address every aspect of the design, construction, and operation of buildings and their equipment around the world. The significant advances in building codes and appliance standards in some jurisdictions over the last decade already demonstrated that they were 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 standards need to be substantially strengthened and adopted for further jurisdictions, building types, and vintages. [9.6, 9.9, 9.10] Table 9.1 summarizes some main findings of the chapter by key mitigation strategy.

9.1 Introduction

This chapter aims to update the knowledge on the building sector since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) from a mitigation perspective. Buildings and activities in buildings are responsible for a significant share of GHG emissions, but they are also the key to mitigation strategies. In 2010, the building sector accounted for approximately 117 Exajoules (EJ) or 32 % of global final energy consumption and 19 % of energy-related CO_2 emissions; and 51 % of global electricity consumption. Buildings contribute to a significant amount of F-gas emissions , with large differences in reported figures due to differing accounting conventions, ranging from around an eighth to a third of all such emissions (9.3.6). The chapter argues that beyond a large emission role, mitigation opportunities in this sector are also significant, often very cost-effective, and are in 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—and they 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 the contribution of Working Group III (WGIII) to the IPCC Fifth Assessment Report (AR5), which focuses 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, 2009; 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:

$$CO_2 = CI \cdot TEI \cdot SEI \cdot A$$

where CO_2 is the emissions from the building sector; (Identity 1) CI is the carbon intensity; (Identity 2) TEI is the technological energy intensity; (Identity 3) SEI is the structural\systemic energy intensity and (Identity 4) A is the activity. For a more precise interpretation of the factors, the following conceptual equation demonstrates the different components:

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

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. Instead of population in the residential sector the Gross Domestic Product (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:

$$CO_2\ mitigation \approx C_{Eff} \cdot T_{Eff} \cdot SI_{Eff} \cdot DR$$

whereby (1) C_{Eff}, or carbon efficiency, entails fuel switch to low-carbon fuels, building-integrated renewable energy sources, and other supply-side decarbonization; (2) T_{Eff}, or technological efficiency, focuses on the efficiency improvement of individual energy-using devices; (3) SI_{Eff}, 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 (4) *DR*, or demand reduction, composes all measures that are beyond technological efficiency and decarbonization 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 use this decomposition as the main organizing/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 9.18 $GtCO_2eq$ in 2010 (Figure 9.1), representing 25 % of total emissions without the Agriculture, Forestry, and Land Use (AFOLU) sector; and 19 % of all global 2010 GHG emissions (IEA, 2012a; JRC/PBL, 2013; see Annex II.8). Furthermore, they account for approximately one-third of black carbon emissions (GEA, 2012), and one-eighth to one-third of F-gas emissions, depending partially on the accounting convention used (UNEP, 2011a; EEA, 2013; US EPA, 2013; JRC/PBL, 2013; IEA, 2012a; see Annex II.8).

Most of GHG emissions (6.02 Gt) 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, which have roughly stagnated during these four decades (Figure 9.1). For instance, residential indirect emissions quintupled and commercial emissions quadrupled.

Figure 9.2 shows the regional trends in building-related GHG emissions. Organisation for Economic Co-operation Development (OECD) countries have the highest emissions, but the growth in this region between 1970 and 2010 was moderate. For least 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.

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 32 % (24 % for residential and 8 % for commercial) of total global final energy use (IEA, 2013), or 32.4 PWh, being one of the largest end-use sectors worldwide. Space heating rep-

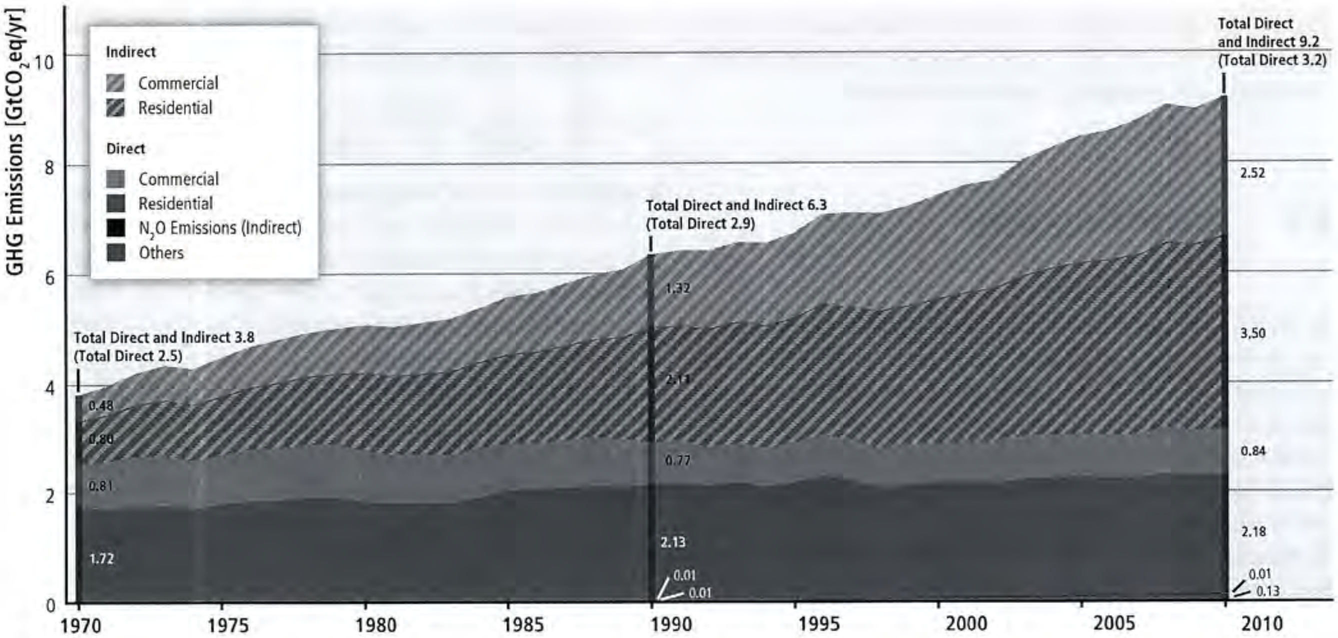


Figure 9.1 | Direct and indirect emissions (from electricity and heat production) in the building subsectors (IEA, 2012a; JRC/PBL, 2013; see Annex II.9).

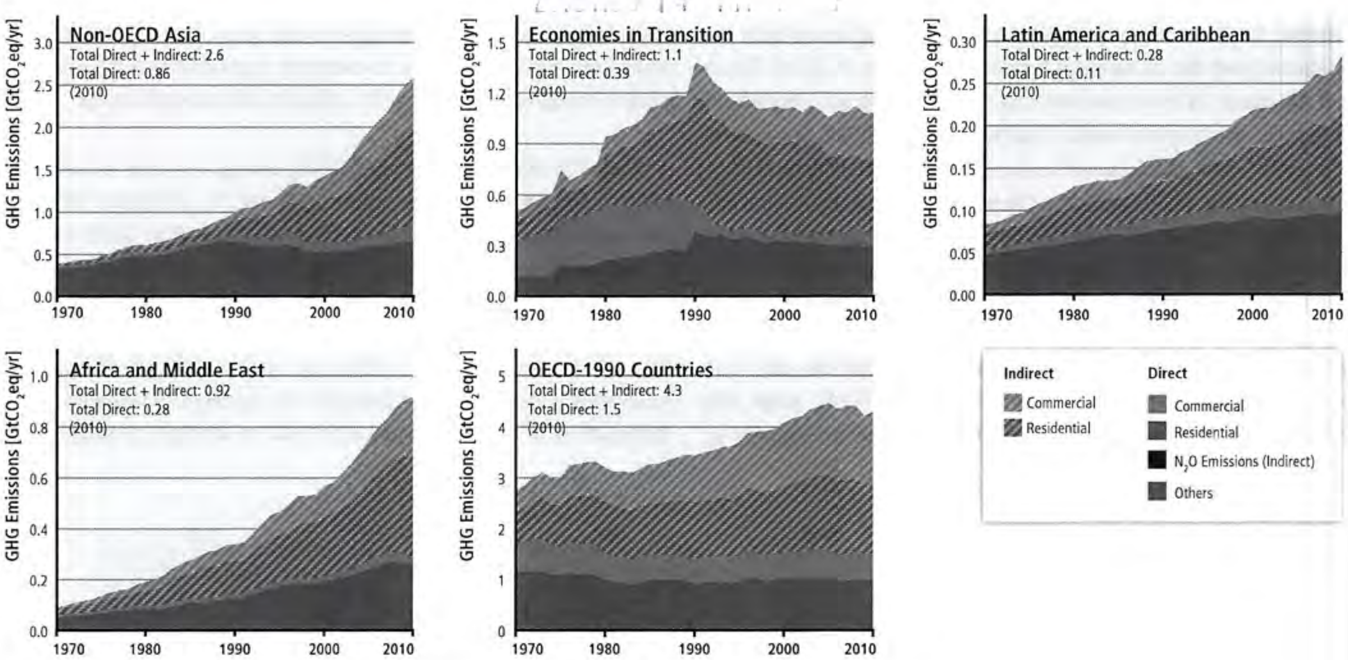


Figure 9.2 | Regional direct and indirect emissions in the building subsectors (IEA, 2012a; JRC/PBL, 2013; see Annex II.9).

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

878 million people with an average 2 USD$_{2010}$ per day of gross national income (The World Bank, 2013) live in the 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). The fast growing rates of new construction, which is 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, and efficient and clean-burning cooking devices (Zhang and Smith, 2007; Duflo et al., 2008; WHO, 2009, 2011; Wilkinson et al., 2009; Hailu, 2012; Pachauri, 2012). Around one-third of the urban population in developing countries in 2010 did not have access to adequate housing (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).

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, and have 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 quality, and health benefits; reduced pressures to expand energy generation capacities in developing regions; productivity, competitiveness, and net employment gains; increased social welfare; reduced 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 (Tirado Herrero et al., 2012; Clinch and Healy, 2001; see also Table 9.7).

resented 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 dynamically growing total emissions, per capita final energy use did not grow substantially over the two decades between 1990 and 2010 in most world regions (see Figure 9.3). This value stagnated in most regions during the period, except for a slight increase in the Former Soviet Union (FSU) and a dynamic growth in North Africa and Middle East (MEA). Commercial energy use has also grown only moderately in most regions on a per capita basis, with more dynamic growth shown in Centrally Planned Asia (CPA), South Asia (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 utilized much more efficiently.

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 an estimated 1.3 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 (IEA, 2012a; Pachauri et al., 2012; see Section 14.3.2.1).The ways these energy services will be provided will significantly influence the development of building related emissions. In addition, migration to

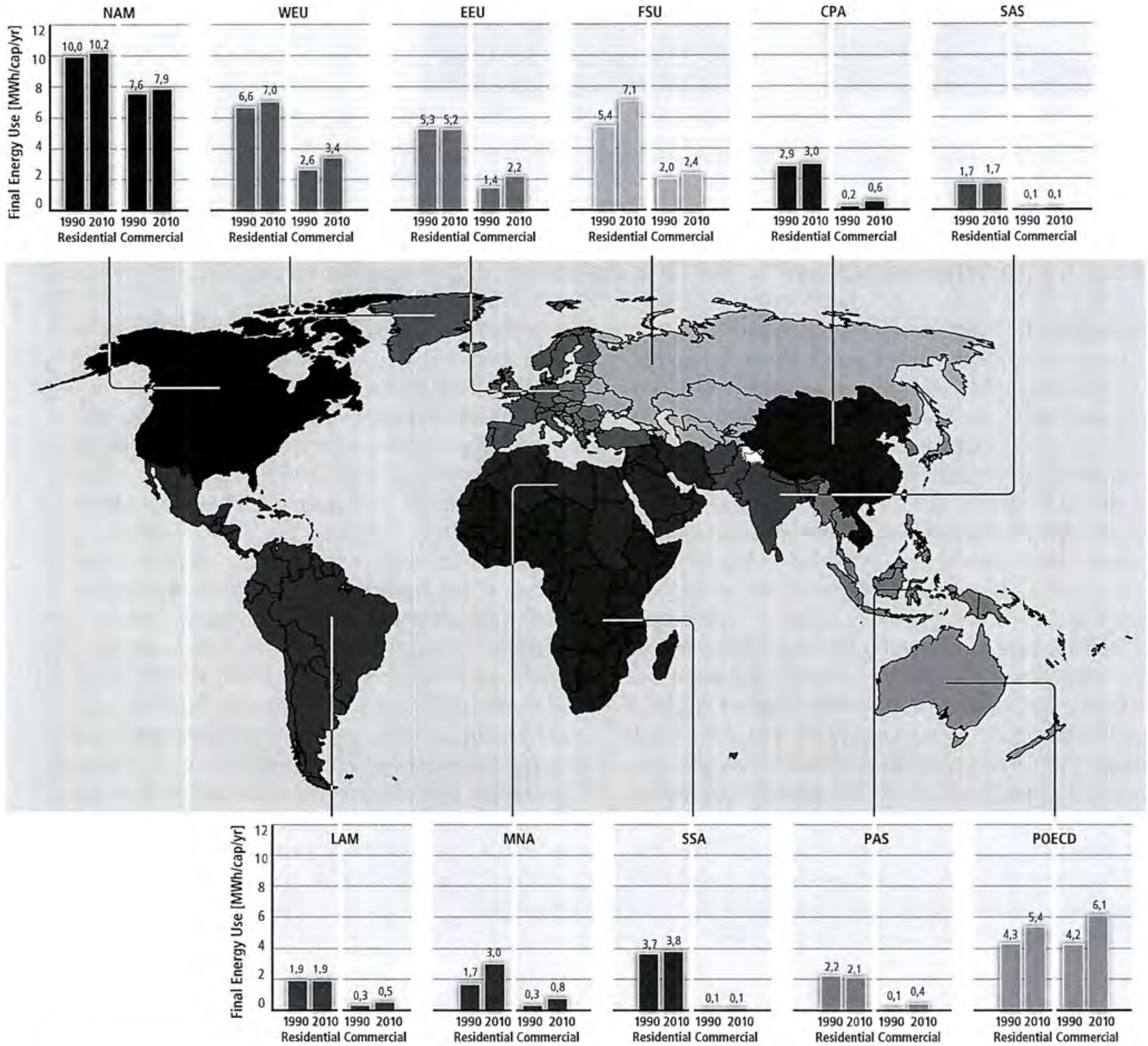


Figure 9.3 | Annual per capita final energy use of residential and commercial buildings for eleven regions (GEA RC11, see Annex II.2.4) in 1990 and 2010. Data from IEA (2012b, 2013).

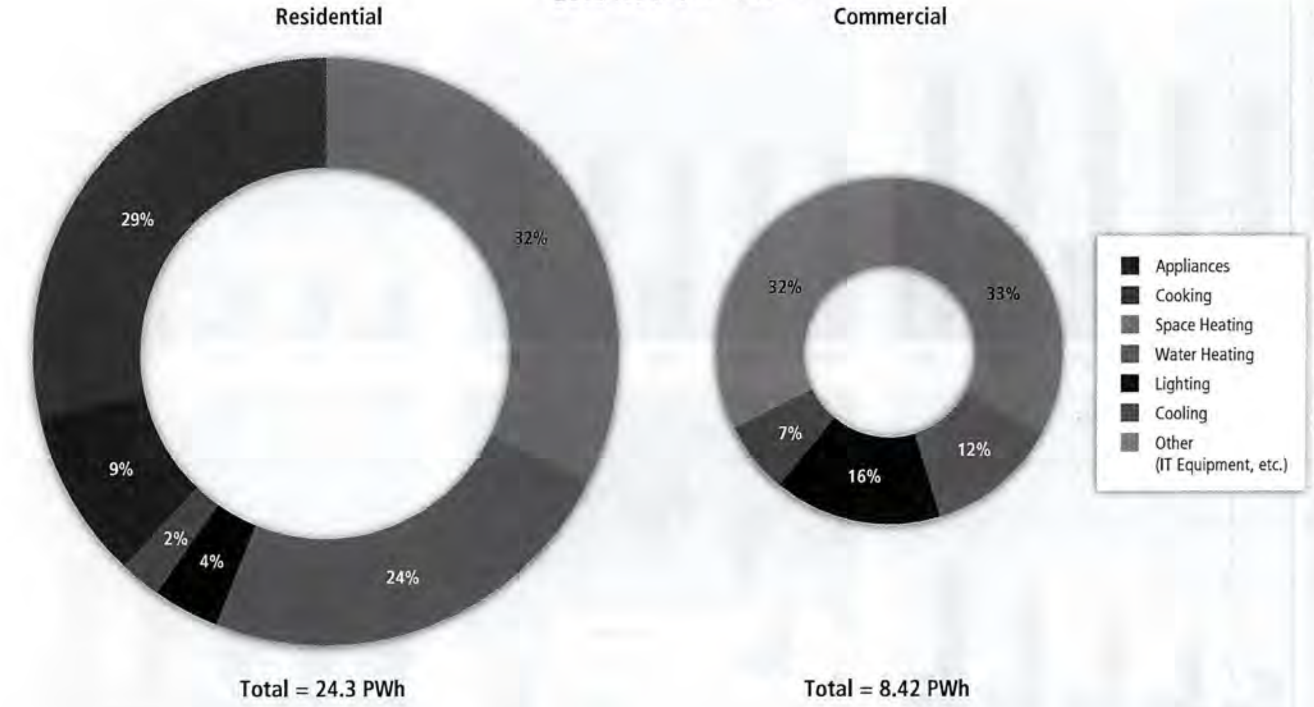


Figure 9.4 | World building final energy consumption by end-use in 2010. Source: IEA (2013).

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—all contribute to significant increases in building energy use. Rapid economic development accompanied by urbanization and shifts from informal to formal housing is propelling significant building activity in developing countries (WBCSD, 2007). As a result, this substantial new construction, which is taking place in these dynamically growing regions represents both a significant risk and opportunity from a mitigation perspective.

9.2.2 Trends and drivers of thermal energy uses in buildings

Figure 9.5 shows projections of thermal energy uses in commercial and residential buildings in the regions of the world from 2010 to 2050. 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. 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:

$$energy_{residential} = h \cdot \frac{p}{h} \cdot \frac{area}{p} \cdot \frac{energy}{area}$$

where $energy_{residential}$ stands for the total residential thermal energy demand, *[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 m^2) per person; and *[energy/area]* is the energy intensity driver, i.e., the annual thermal energy consumption (usually kWh) per unit of floor area, also referred to as specific energy consumption. For commercial buildings, the heating and cooling use is decomposed as

$$energy_{commercial} = GDP \cdot \frac{area}{GDP} \cdot \frac{energy}{area}$$

where $energy_{commercial}$ stands for the total commercial thermal energy demand, *[GDP]*, i.e., nominal Gross Domestic Product is the activity driver; *[area/GDP]* is the use intensity driver and *[energy/area]* is the energy intensity driver, the annual thermal energy consumption (in kWh) per unit of floor area (in m^2), also referred to as specific energy consumption. Figures 9.6 and 9.7 illustrate the main trends in heating and cooling energy use as well as its drivers globally and by region.

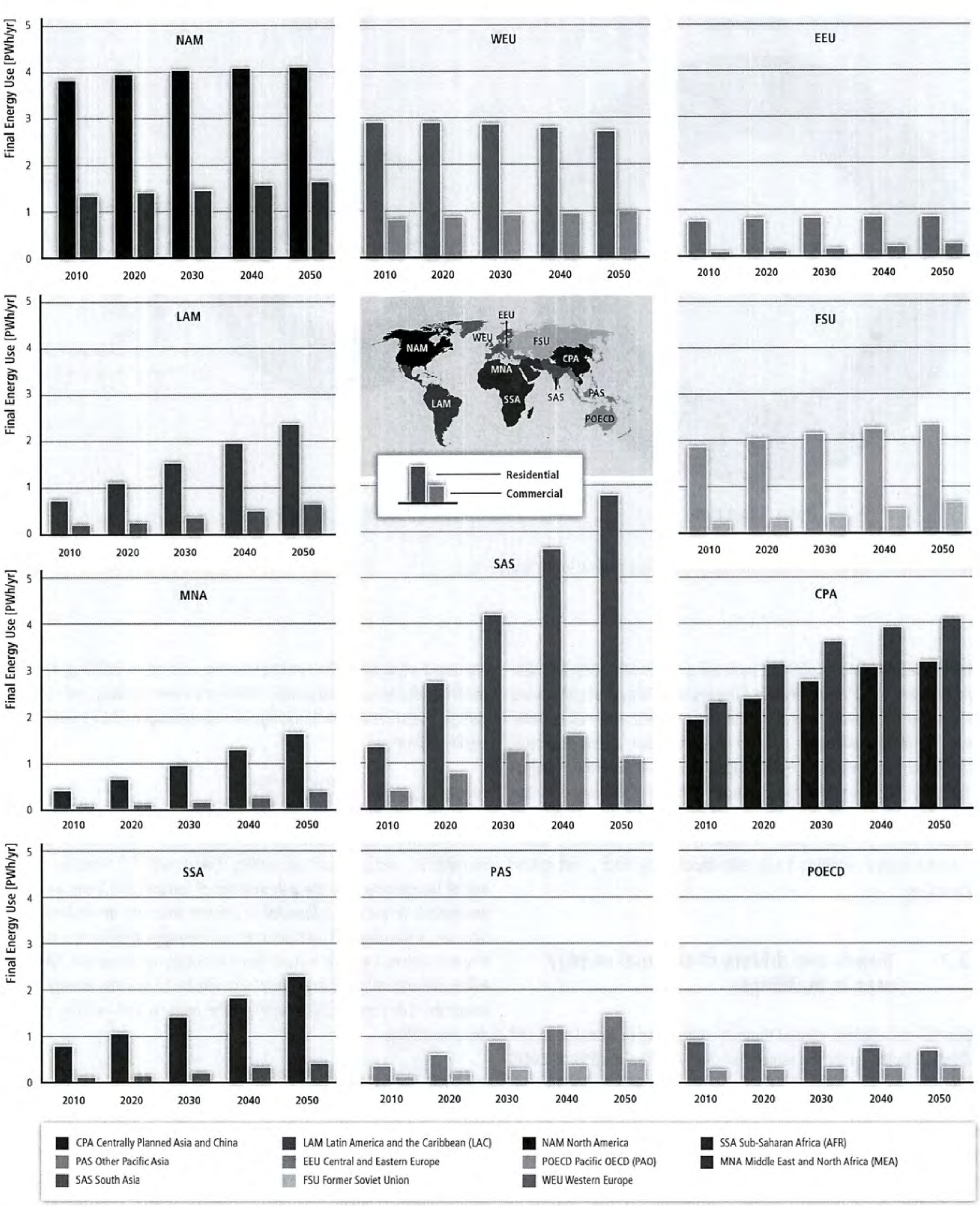


Figure 9.5 | Total annual final thermal energy consumption (PWh/yr) trends in eleven world regions (GEA RC11, see Annex II.2.4) for residential and commercial buildings (GEA region abbreviation added in brackets where different from abbreviation used in this report). Historical data (1980–2000) are from IEA statistics; projections (2010–2050) are based on a frozen (i.e. unchanged over time) efficiency scenario (Ürge-Vorsatz et al., 2013).

Heating and cooling energy use in residential and commercial buildings is expected to grow by 79 % and 84 %, 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 of *area/GDP* is 61 %, while energy/area is expected to stay constant over the period 2010–2050. 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). These figures indicate that in some regions (e.g., NAM and WEU), strong energy building policies are already resulting in declining or stagnating total energy use trends despite the increase in population and service levels.

9.2.3 Trends and drivers in energy consumption of appliances in buildings

In this chapter, we use the word 'appliances' in a broad sense, covering all electricity-using non-thermal equipment in buildings, including lighting and ICT. Traditional large appliances, such as refrigerators and washing machines, are still responsible for most household electricity consumption (IEA, 2012c) albeit with a falling share related to the equipment for information technology and communications (including home entertainment) accounting in most countries for 20 % or more 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., 2013b):

$$energy = \sum_{a} h \cdot \frac{n}{h} \cdot \frac{energy}{n}$$

Where $\sum_a$ 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/yr used per appliance). The number of appliances used increased around 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. In addition, while fans are a minor end-use in most OECD countries, they continue to be extremely important in the warm developing countries.

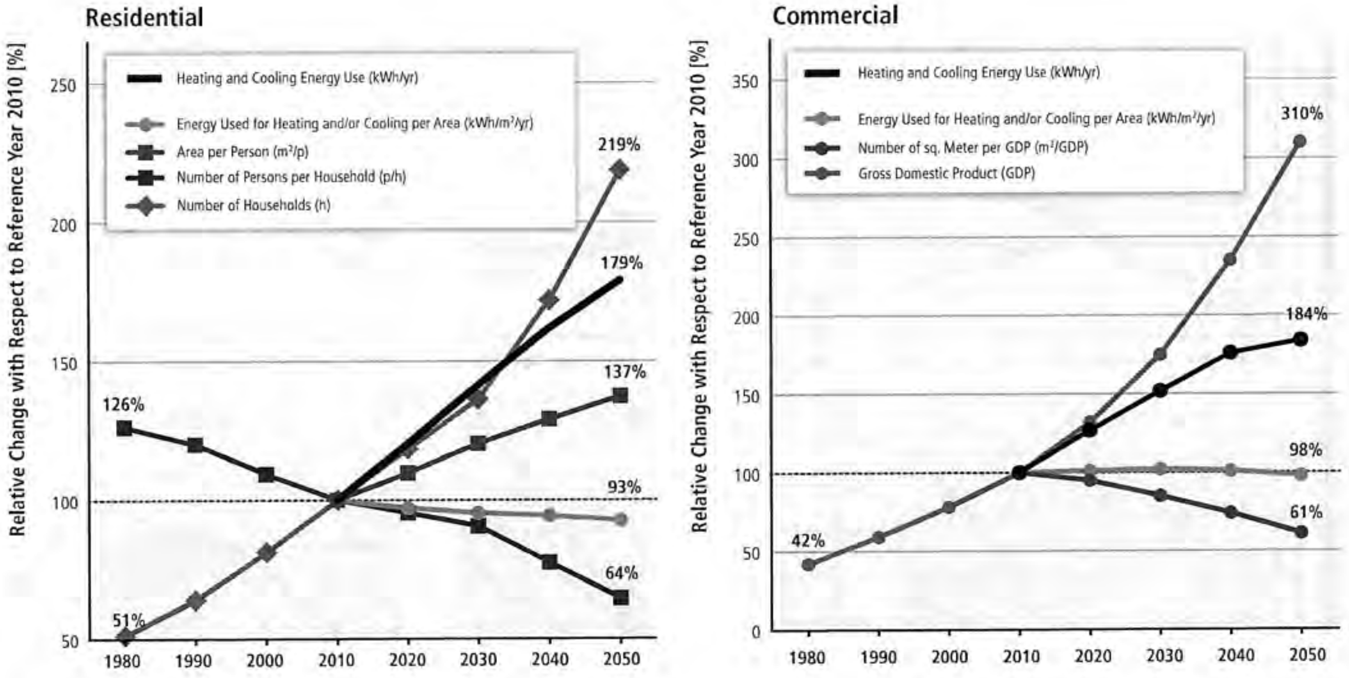
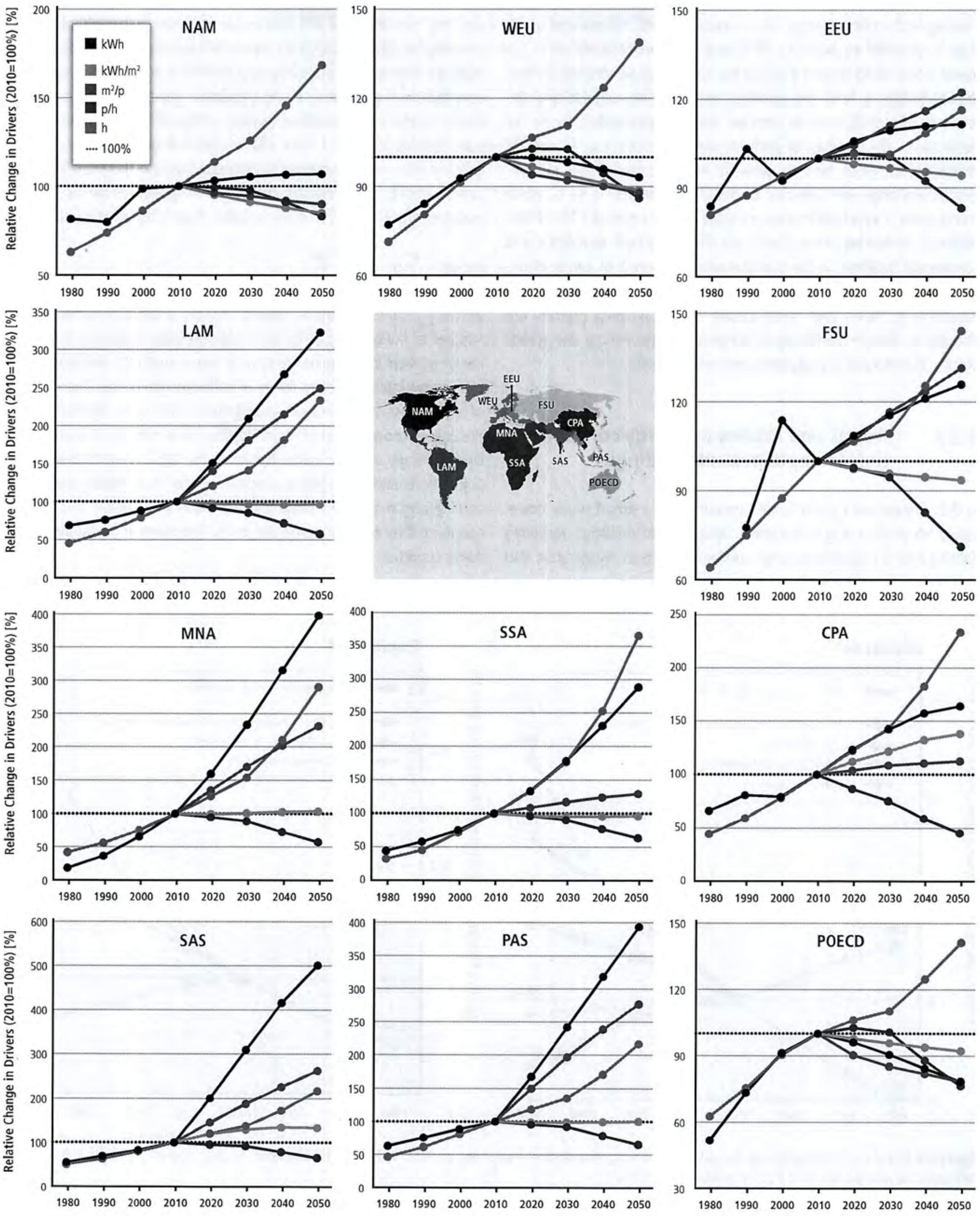


Figure 9.6 | Trends in the different drivers for global heating and cooling thermal energy consumption in residential and commercial buildings. Source: Ürge-Vorsatz et al. (2013) with projection data (2010–2050) from frozen efficiency scenario.


NAM
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SAS
PAS
LAM
SSA
POECD
Relative Change in Drivers (2010=100%) [%]
1980 1990 2000 2010 2020 2030 2040 2050
200 150 100 50
150 120 90 60
350 300 250 200 150 100 50 0
400 350 300 250 200 150 100 50 0
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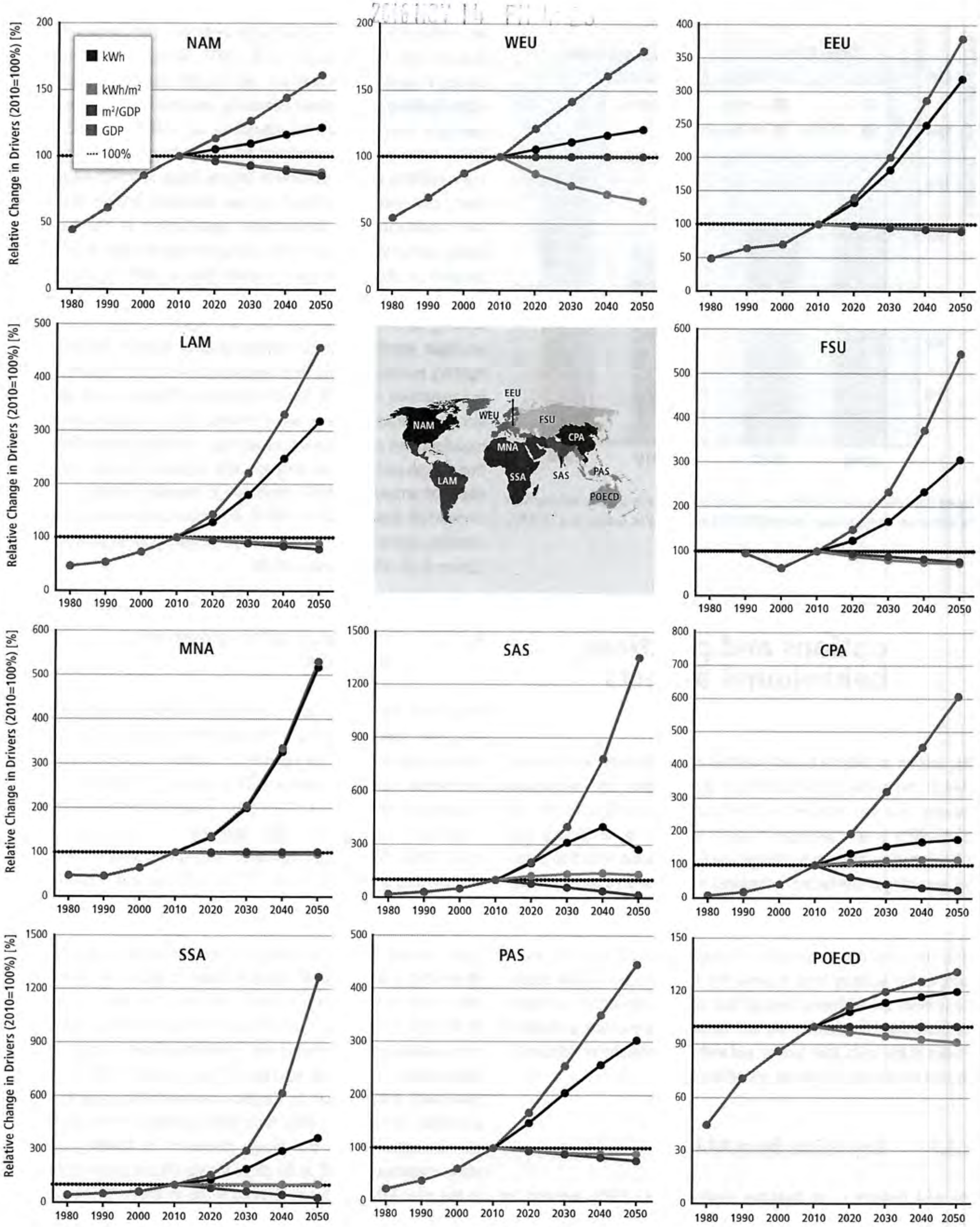


Figure 9.7 | Trends in the drivers of heating and cooling thermal energy consumption of residential (first page) and commercial (this page) buildings in world regions (GEA RC11, see Annex II.2.4). Source: Ürge-Vorsatz et al. (2013) with projection data (2010–2050) from frozen efficiency scenario.

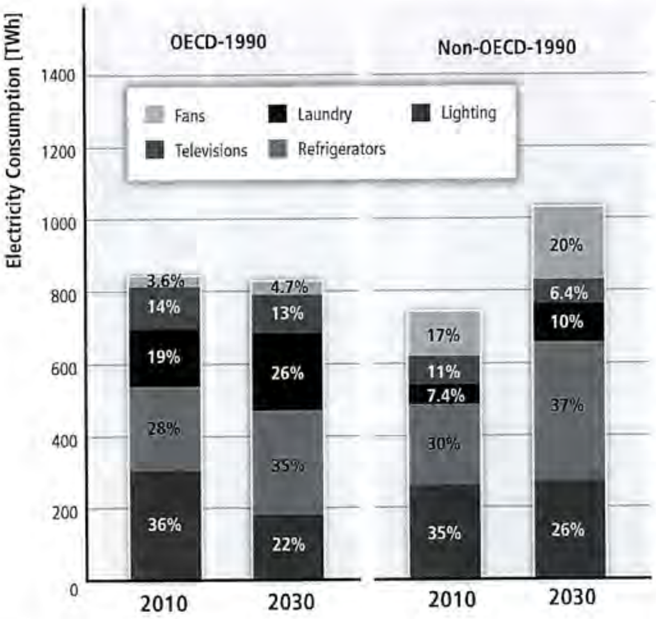


Figure 9.8 | Residential electricity consumption by end-use in a policy scenario from the Bottom-Up Energy Analysis System (BUENAS) model. Source: Cabeza et al. (2013b).

9.3 Mitigation technology options and practices, behavioural aspects

This section provides a broad overview at the strategic and planning level of the technological options, design practices, and behavioural changes that can achieve large reductions in building energy use (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 in this section, 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.

9.3.1 Key points from AR4

The AR4 Chapter 6 on Buildings (Levine et al., 2007) contains an extensive discussion of the wide range of techniques and designs to reduce energy use in new buildings. Savings at the system level are generally larger than for individual devices (pumps, motors, fans, heaters, chillers, etc.), as are related net investment-cost savings—usually several times higher (Levine et al., 2007; Harvey, 2008). Integrated Design Process (IDP) allows for the systemic approach, which optimizes building performance iteratively, and involves all design team members from the start (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 optimization opportunities in the following design and building phases, thus losing key opportunities for the optimization of whole buildings as systems (Lewis, 2004). As discussed in AR4, essential steps in the design of low-energy buildings are: (1) building orientation, thermal mass, and shape; (2) high-performance envelope specification; (3) maximization of passive features (daylighting, heating, cooling, and ventilation); (4) efficient systems meeting remaining loads; (5) highest possible efficiencies and adequate sizing of individual energy-using devices; and (6) proper commissioning of systems and devices. Cost savings can substantially offset additional high-performance envelope and higher-efficiency equipment costs, of 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

Since AR4, there have been important performance improvements and cost reductions in many relevant technologies, and further significant improvements are expected. Examples include (1) daylighting and electric lighting (Dubois and Blomsterberg, 2011); (2) household appliances (Bansal et al., 2011); (3) insulation materials (Baetens et al., 2011; Korjenic et al., 2011; Jelle, 2011); (4) heat pumps (Chua et al., 2010); (5) indirect evaporative cooling to replace chillers in dry climates (Jiang and Xie, 2010); (6) fuel cells (Ito and Otsuka, 2011); (7) advances in digital building automation and control systems (NBI, 2011); and (8) 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. In addition to the new technologies, practitioners have also increasingly applied more established technology and knowledge both in new building construction and in the existing building retrofits. These practices have been driven in part by targeted demonstration programmes in a number of countries. They have been accompanied by a progressive strengthening of the energy provisions of building codes in many countries, as well as by plans for significant further tightening 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.

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 behavioural changes.

End Use	On-site C-Free Energy Supply[1]	Device Efficiency	System Efficiency	Behavioural 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: [1] 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 spin-up (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/m²/yr to 15 kWh/m²/yr (Passive House standard, Section 9.3.2). [6] Typical value; 2 °C 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. [10] 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. [11] Shorter showers, switch from bathing to showering, and other hot-water-conserving behaviour. [12] 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). [13] 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. [14] Replacement of North American units with units incorporating all potential efficiency improvements; Table 9.4. [15] Reduction (even elimination) of cooling loads through better building orientation & envelopes, provision for passive cooling, and reduction of internal heat gains (Harvey, 2007). [16] Section 9.3.9. Fans during tolerable brief periods eliminating cooling equipment in moderately hot climates. [17] Cooking range, various ovens. [18] Range pertains to various kinds of ovens; Table 9.4. [19] 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. [21] 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., 2005; 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/m²/yr (Harvey, 2013) to 5–15 kWh/m²/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 ft³vs 18.5 ft³ (350 litres, 350 kWh/yr vs 520 litres, 500 kWh/yr) refrigerator-freezers or 18.5 vs 30.5 ft³ (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 one-third to half 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.

9.3.3 Exemplary New Buildings

This section 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 (kWh/m²/yr)—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

The energy performance of new buildings have improved considerably since AR4, as demonstrated in Table 9.3, which summarizes the specific energy consumption for floor-area driven final energy uses by climate type or region.

A number of voluntary standards for heating energy use have been developed in various countries for *residential buildings* (see Table 1 in Harvey, 2013). The most stringent of standards with regard to heating requirements is the Passive House standard, which prescribes a

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.

heating load (assuming a uniform indoor temperature of 20°C) 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 significant additional floor area that meets or exceeds 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 where existing buildings have little to no insulation. 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 use 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; Zhang and Yoshino, 2010; Lin and Chuah, 2011), Vietnam (Nguyen et al., 2011), Brazil (Grigoletti et al., 2008; Andreasi et al., 2010; Cândido 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 (energy that must be removed from, e.g., the air inside a building) 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., 2011) 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/m^2/yr during the first year of operation to 150 kWh/m^2/yr during the third year (with a predicted improvement to 110 kWh/m^2/yr 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 as PV, wind turbines, or solar thermal) that, over the year, generate as much energy as is 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). 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. 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 (1) the feasibility of NZEBs; (2) minimizing the cost of attaining an NZEB, where feasible; (3) 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; (4) the sustainability of NZEBs; (5) lifecycle energy use; and (6) impact on energy use of alternative uses or treatments of roofs.

To create 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, for example, NZEB is possible in office buildings of up to five stories if internal heat gains and lighting and HVAC loads are aggressively reduced (Phillips et al., 2009).

9.3.3.4 Incremental cost of low-energy buildings

A large number of published studies on 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 to illustrate some of the main findings.

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 66–265 USD_{2010}/m^2) as compared to standard construction. A variety of locations in the United States, show additional costs of houses that achieve 34–76 % reduction in energy use of about 30–163 USD_{2010}/m^2–this excludes solar PV for both savings and costs (Parker, 2009). 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 66–265 USD_{2010}/m^2) relative to a design that meets the 2006 mandatory regulations—which have since been strengthened (Davis Langdon and Element Energy, 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 lifecycle 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: (1) 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); (2) 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); (3) 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 (4) 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 dominant 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.

Available studies (such as in Table 9.4) indicate that the incremental cost of low-energy buildings in the *commercial sector* is less than in the residential sector, due to the greater opportunities for simplification of the HVAC system, and that it is possible for low-energy commercial buildings to cost less than conventional buildings. In particular, there are a number of examples of educational and small office buildings that have been built to the Passive House standard at no additional cost compared to similar conventional or less-stringently low-energy local buildings (Anwyl, 2011; Pearson, 2011). The Research Support Facilities Building (RSF) at the National Renewable Energy Laboratory (NREL) 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) present 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 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 (Harvey, 2013). The keys to delivering low-energy buildings at zero or little additional cost are through implementation of the Integrated Design Process (IDP; 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.

9.3.4 Retrofits of existing buildings

As buildings are very long-lived and a large proportion 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 are: (1) For detached single-family homes, the most comprehensive retrofit packages have achieved reductions in total energy use by 50–75 %; (2) 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; (3) 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; (4) in commercial buildings, savings in total HVAC energy use achieved through upgrades to equipment and control systems, but without changing the building envelope, are typically on the order of 25–50 %; (5) eventual re-cladding of building façades—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 (6) 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 potentials (with comprehensive insulation and window upgrades, air sealing, and implementation of mechanical ventilation with heat recovery) reductions in heating energy requirements of 50–75 % in single-family housing and 50–90 % in multi-family housing at costs of about 100–400 $\text{USD}_{2010}/\text{m}^2$ above that which would be required for a routine renovation. For a small selection of these studies, 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 United States 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 lifecycle 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 – 0.09 USD_{2010}/kWh (appliance upgrades) and +0.45 USD_{2010}/kWh (façade retrofit). Polly et al. (2011) present a method for determining optimal residential energy efficiency retrofit packages in the United States, and identify near-cost-neutral packages of measures providing between 29 % and 48 % energy savings across eight 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^2/yr.

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; Labanca and Paolo, 2013) due to polices such as efficiency standards, labels, and subsides and technological progress. Improvements are also appearing in developing countries such as China (Barthel and Götz, 2013) and less developed countries, such as Ghana (Antwi-Agyei, 2013). Old

Table 9.4 | Summary of estimates for extra investment cost required for selected very low-/zero-energy buildings.

Case	Location	Type	Energy performance	Extra investment costs	CCE (USD$_{2010}$/kWh)	References
Passive House Projects	Central Europe	New	Passive House standard	5–8 % (143–225 USD$_{2010}$/m^2)	–	(Bretzke, 2005; Schnieders and Hermelink, 2006)
5 Passive Houses	Belgium	New	62 kWh/m^2/yr total	16 % (252 USD$_{2010}$/m^2)	–	(Audenaert et al., 2008)
Passive House apartment block	Vienna	New	Passive House standard	5 % (69 USD$_{2010}$/m^2)	–	(Mahdavi and Doppelbauer, 2010)
12 very low or net zero-energy houses	United States	New		0.07–0.12 USD$_{2010}$/kWh (CCE)	–	(Parker, 2009)
10 buildings in the SolarBauprogramme	Germany	New	< 100 kWh/m^2/yr primary energy vs. 300–600—conventional	Comparable to the difference in costs between alternative standards for interior finishes	–	(Wagner et al., 2004)
High performance commercial buildings	Vancouver	New	100 kWh/m^2/yr total vs. 180—conventional	10 % lower cost	–	(McDonell, 2003)
Offices and laboratory, Concordia University	Montreal	New		2.30 %	–	(Lemire and Charneux, 2005)
Welsh Information and Technology Adult Learning Centre (CaolfanHyddgen)	Wales	New	Passive House standard	No extra cost compared to BREEAM 'Excellent' standard	–	(Pearson, 2011)
Hypothetical 6,000 m^2 office building	Las Vegas	New	42 % of energy savings	USD$_{2010}$ 2,719	–	(Vaidya et al., 2009)
10-story, 7,000 m^2 residential building	Denmark	New	14 kWh/m^2/yr (heating) vs. 45	3.4 % (115 USD$_{2010}$/ m^2)	–	(Marszal and Heiselberg, 2009)
Leslie Shao-Ming Sun Field Station, Stanford University	California	New	NZEB	4–10 % more based on hard construction costs	–	(NBI, 2011)
Hudson Valley Clean Energy Headquarters	New York	New	NZEB	665 USD$_{2010}$/month in mortgage payments but saves 823 USD$_{2010}$/month in energy costs	–	(NBI, 2011)
IAMU Office	Ankeny, IA	New	NZEB	None	–	(NBI, 2011)
EcoFlats Building	Portland, OR	New	NZEB	None	–	(NBI, 2011)
10-story, 7,000 m^2 residential building	Denmark	New	NZEB	24 % (558 USD$_{2010}$/m^2)	–	(Marszal and Heiselberg, 2009)
Toronto towers	Toronto	Retrofit	194/95 %	259 USD$_{2010}$/m^2	0.052	(Kesik and Saleff, 2009)
Multi-family housing	EU	Retrofit	62–150/52 %–86 %	53–124 USD$_{2010}$/m^2	0.014–0.023	(Petersdorff et al., 2005)
Terrace housing	EU	Retrofit	97–266/59 %–84 %	90–207 USD$_{2010}$/m^2	0.13–0.023	(Petersdorff et al., 2005)
High-rise housing	EU	Retrofit	70 %–81 %	2.5–5.8 USD$_{2010}$/m^2/yr	0.018–0.028	(Waide et al., 2006)
1950s MFH	Germany	Retrofit	82–247/30 %–90 %	48–416 USD$_{2010}$/m^2	0.023–0.065	(Galvin, 2010)
1925 SFH	Denmark	Retrofit	120	217 USD$_{2010}$/m^2	0.071	(Kragh and Rose, 2011)
1929 MFH	Germany	Retrofit	140–200/58 %–82 %	167–340 USD$_{2010}$/m^2	0.060–0.088	(Hermelink, 2009)
19th century flat	UK	Retrofit	192–234/48 %–59 %	305–762 USD$_{2010}$/m^2	0.068–0.140	(United House, 2009)

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. The saving potentials identified 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 et al., 2013a), while the most efficient televisions awarded under the Super-efficient Equipment and Appliance Deployment (SEAD) initiative use 33–44 % less electricity than similar televisions (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 wealth. This will occur 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 et al., 2013b). This could yield energy savings of

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 the United States (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 LED backlighting (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 ≤0.11 USD_{2010}/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 United States average to European heat pump dryer (820 kWh/yr vs 380 kWh/yr)	(Werle et al., 2011)
Standby loads	Potential of < 0.005 W for adapters and chargers, < 0.05 for large appliances ('zero' in both cases) (typical mid 2000s standby power draw: 5–15 W)	(Harvey, 2010; Matthews, 2011), (Harvey, 2010) for mid 2000s data
Air conditioners	COP (a measure of efficiency) of 2.5–3.5 in Europe and United States, 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	(Letschert et al., 2012; Sathaye et al., 2013)
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 the USA 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)

2600 TWh/yr by 2030 between the EU, United States, China and India (Letschert et al., 2013a). 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 levels above all the other commercially available light source (Aman et al., 2013), including high efficiency fluorescent lamps.

9.3.6 Halocarbons

The emissions of F-gases (see Chapter 1 Table 1.1 and Chapter 5.3.1) related to the building sector primarily originate from cooling/refrigeration and insulation with foams. The sector's share of total F-gas emissions is subject to high variation due to uncertainties, lack of detailed reporting and differences in accounting conventions. The following section discusses the role of the buildings sector in F-gas emissions under these constraints.

F-gases are used in buildings through several types of products and appliances, including refrigeration, air conditioning, in foams (such as for insulation) as blowing agents, fire extinguishers, and aerosols. The resulting share of the building sector in the total F-gas emissions, similarly to indirect CO_2 emissions from electricity generation, depends on their attribution. Inventories, such as EDGAR (JRC/PBL, 2013), are related to the production and sales of these gases and differing accounting conventions attribute emissions based on the point of their use, emissions, or production (UNEP, 2011a; EEA, 2013; US EPA, 2013). IPCC emission categories provide numbers to different sources of emission but do not systematically attribute these to sectors. Attribution can be done using a production or consumption perspective, rendering different sectoral shares (see Chapter 5.2.3.3). Compounding this variation, there are uncertainties resulting from the lack of attribution of the use of certain emission categories to different sectors they are used in and uncertainties in reported figures for the same emissions by different sources.

As a guidance on the share of F-gases in the building sector, for example, EDGAR (JRC/PBL, 2013; Annex II.9) attributed 12 % of direct F-gas emissions to the building sector in 2010 (JRC/PBL, 2013; Annex II.9). Of a further share of 22.3 % of F-gas emissions (21 % from HFC and SF6 production and 1.3 % from foam blowing) a substantial part can be allocated to the buildings sector. The greatest uncertainty of attribution of IPCC categories to the buildings sector is the share of Refrigeration and Air Conditioning Equipment (2F1a). This totals to up to one-third for the share of (direct plus indirect) buildings in F-gas emissions.

As another proxy, EDGAR estimates that HFCs represent the largest share (GWP adjusted) in the total F-gas emissions, at about 76 % of total 2010 F-gas emissions (JRC/PBL, 2013). Global HFC emissions are reported to be 760 $MtCO_2eq$ by EDGAR (JRC/PBL, 2013); and 1100 $MtCO_2eq$ by the US EPA (2010). These gases are used mostly (55 % of total in 2010) in refrigeration and air-conditioning equipment in homes, other buildings and industrial operations (UNEP, 2011a).

While F-gases represent a small fraction of the current total GHG emissions—around 2 % (see Chapter 1.2 and Chapter 5.2), their emissions are projected to grow in the coming decades, mostly due to increased demand for cooling and because they are the primary substitutes for ozone-depleting substances (US EPA, 2013).

Measures to reduce these emissions include the phase-out of HFCs and minimization of the need for mechanical cooling through high-performance buildings, as discussed in the following sections. The use of F-gases as an expanding agent in polyurethane foam has been banned in the EU since 2008, and by 2005, 85 % of production had already been shifted to hydrocarbons (having a much lower GWP). In Germany, almost all new refrigerators use natural refrigerants (isobutane, HC-600a, and propane, HC-29), which have great potential to reduce emissions during the operation and servicing of HFC-containing equipment (McCulloch, 2009; Rhiemeier and Harnisch, 2009). Their use in insulation materials saves heating and cooling related CO_2 emissions and thus their use in these materials still typically has a net benefit to GHG emissions, but a lifecycle assessment is required to determine the net effect on a case-by-case basis.

9.3.7 Avoiding mechanical heating, cooling, and ventilation systems

In many parts of the world, high-performance mechanical cooling systems are not affordable, especially those used for residential housing. 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 (Nguyen et al., 2011) experienced conditions warmer than 31 °C only 6 % of the time. The natural and passive control system of traditional housing in Kerala, India has been shown to maintain bedroom temperatures of 23–29 °C even as outdoor temperatures vary from 17–36 °C on a diurnal time scale (Dili et al., 2010). While these examples show that vernacular architecture can be an energy efficient option, in order to promote the technology, 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). In some cases, 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, and it plays an important role for space heating, production of hot water, and for cooking in many developing countries (IEA, 2012d). Compared to open fires, advanced biomass stoves provide fuel savings of 30–60 % and reduce indoor air pollution levels by 80–90 % for models with chimneys (Ürge-Vorsatz et al., 2012b). For example, in the state of Arunachal Pradesh, advanced cookstoves with an efficiency of 60 %, has been used in place of traditional cookstoves with an efficiency of 6–8 % (Rawat et al., 2010). Gasifier and biogas cookstoves have also undergone major developments since AR4.

9.3.9 Embodied energy and building materials lifecycle

Research published since AR4 confirms that the total lifecycle 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 lifecycle assessment, lifecycle energy analysis, and material flow analysis in buildings (conventional and traditional) can be found in Cabeza et al. (2013a). 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 largely 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 windows that can be opened for natural ventilation, part time & part space control of indoor environment (thermal and lighting), and variably controllable indoor thermal parameters (temperature, humidity, illumination and fresh air). These are traditional approaches to obtain a suitable indoor climate and thermal comfort. However, since the spread of globalized supply of commercial thermal conditioning, heating/cooling solutions tend towards fully controlled indoor climates through mechanical 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 lifestyles in buildings, in particular through the use of 'part-time' and 'part-space' indoor climate conditioning, using mechanical systems only for the remaining needs when passive approaches cannot meet comfort demands. Such pathways can reach the energy use levels below 30 kWh$_e$/m^2/yr as a world average (TUBESRC, 2009; Murakami et al., 2009), as opposed to the 30–50 kWh$_e$/m^2/yr achievable through building development pathways utilizing fully automatized full thermal conditioning (Murakami et al., 2009; Yoshino et al., 2011).

Behaviour and local cultural factors can drive basic energy use practices, such as how people and organizations adjust their thermostats during different times of the year. During the cooling season, increasing the thermostat setting from 24 °C to 28 °C 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 23 °C to 27 °C 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 attire standards, for example Japan's 'Cool Biz' initiative to relax certain business dress codes to allow higher thermostat settings (GEA, 2011).

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^2/yr. The use difference is

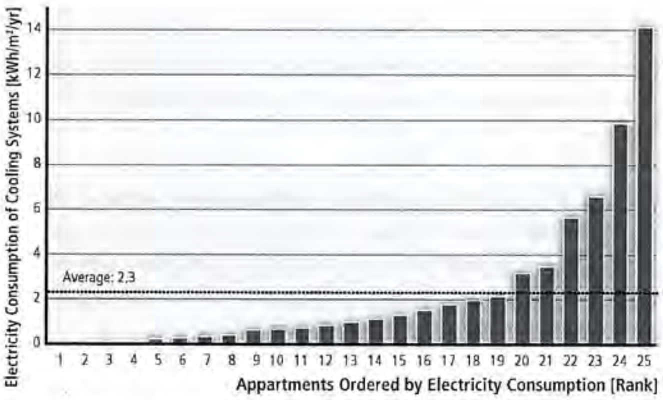


Figure 9.9 | Annual measured electricity per unit of floor space for cooling in an apartment block in Beijing (Zhang et al., 2010).

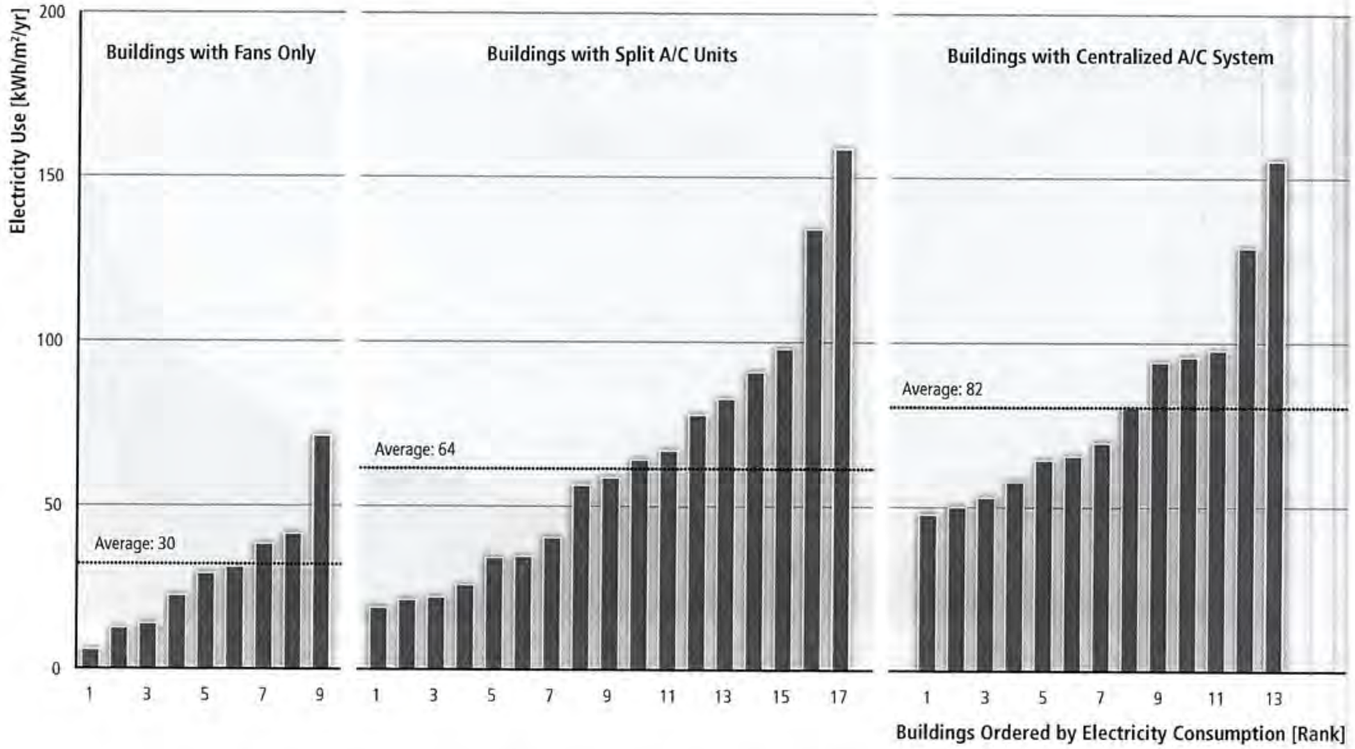


Figure 9.10 | Annual total electricity use per unit of floor space of buildings on a university campus in Beijing, China, 2006 (Zhang et al., 2010).

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 United States) consuming about 600–1000 kWh/yr, while drying naturally is dominant in developing and even in many developed countries (Grinshpon, 2011).

Quantitative modelling 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 United States, for example, 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 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). For more on consumption, see also Section 4.4.

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 vs. 12h/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.

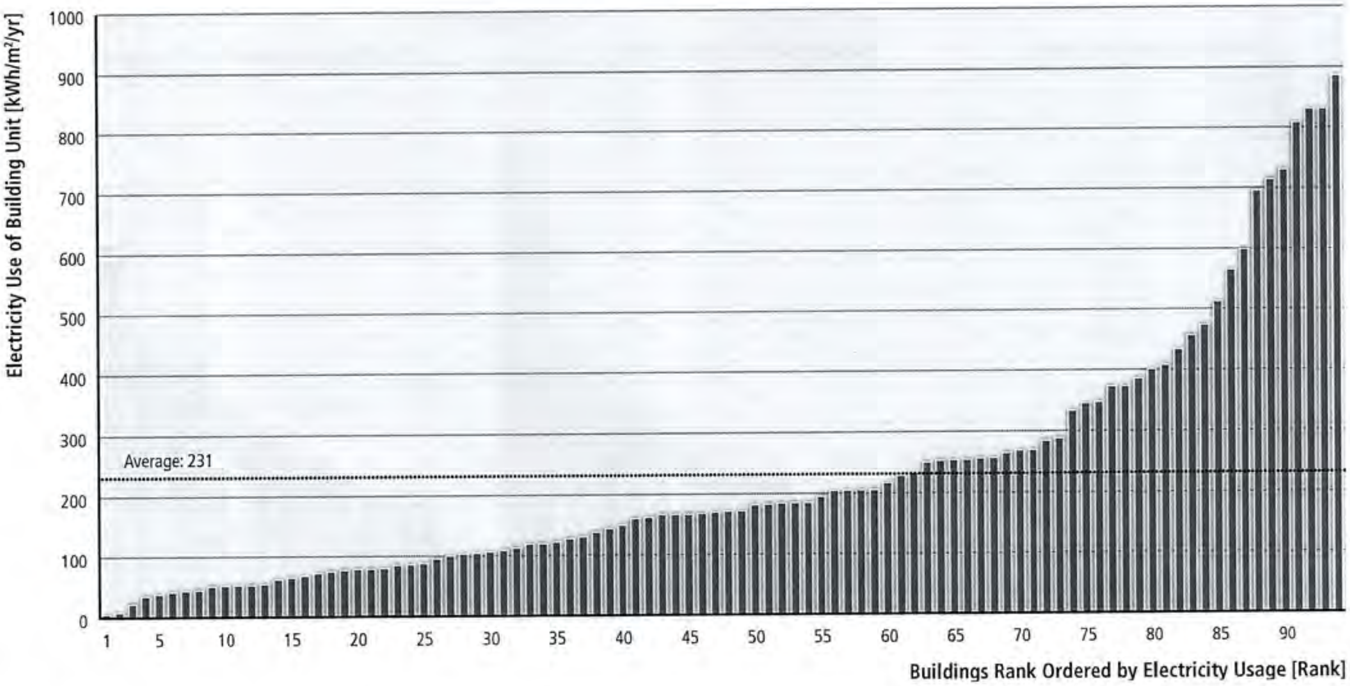


Figure 9.11 | Annual unit area electricity use per unit of floor space of buildings on a university campus in Philadelphia, USA, 2006 (Zhang et al., 2010).

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 et al., 2012a). Greater compactness often has tradeoffs 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. While 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 engines 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 energy source 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 decarbonization 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 decarbonization (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 et al., 2010a). 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 decarbonization (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. Electricity use, 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 increasingly need 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 fluctuations and can be implemented by sensible heat (e.g., changing the 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).

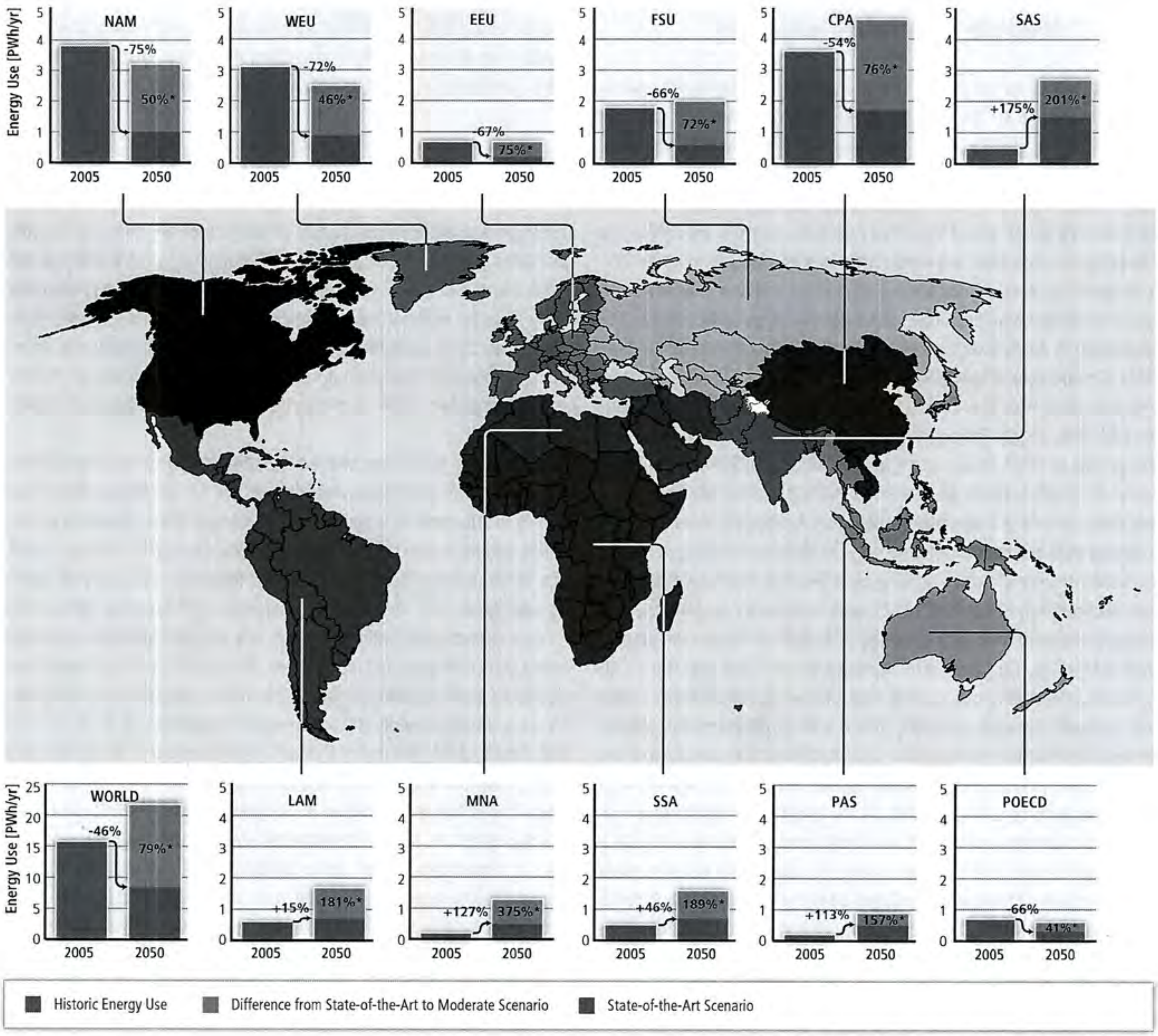
9.4.2 Path dependencies and lock-in

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 to 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).

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 et al., 2012a). 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 et al., 2012a) 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, 2009; Hunt and Watkiss, 2011), while passive cooling approaches become less effective (Artmann et al., 2008; Chow and Levermore, 2010). Under a +3.7 °C scenario by 2100, the worldwide reduction in heating energy



*Lock-in Risk of Sub-Optimal Scenario Realative to Energy Use in 2005.

Figure 9.12 | Final building heating and cooling energy use in 2005 and in scenarios from the Global Energy Assessment (GEA) for 2050, organized by eleven regions (Ürge-Vorsatz et al., 2012a). Notes: Green bars, indicated by arrows with numbers (relative to 2005 values), represent the opportunities through the GEA state-of-the-art scenario, while the yellow bars with black numbers show the size of the lock-in risk (difference between the sub-optimal and state-of-the-art scenario). Percent figures are relative to 2005 values. For region definitions see Annex II.2.4.

demand due to climate change may reach 34 % in 2100, while cooling demand may increase by ≥ 70 %; net energy demand could 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, 2009). Other regional and national studies (Mansur et al., 2008; van Ruijven et al., 2011; Wan et al., 2011; Xu et al., 2012a) reveal the same general tendencies, with energy consumption in buildings shifting from fossil fuels to electricity and affecting peak loads (Isaac and Van Vuuren, 2009; 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 (2009) shows a net increase in residential emissions of ≥ 0.3 Gt C (≥ 1.1 Gt CO_2eq) 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 minimizing energy consumption for operation, mitigating GHG emissions, providing adaptive capacity and resilience to the building stock, reducing costs for maintaining comfort, minimizing the vulnerability of occupants to extreme weather conditions, and 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 urbanization 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., 2009; Oleson et al., 2010; Millstein and Menon, 2011). Akbari et al., (2009, 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 tCO_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 78 $GtCO_2$ (Menon et al., 2010). Increasing the albedo of a 1 m^2 area by 0.01 results in a global temperature reduction of 3×10^{-15} K and offsets emission of 7 kg 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, an important question is to determine what portion of the stock they apply to, and what the overall potential is if we consider the applicability, feasibility, and replacement dynamics, together with other constraints (Wada et al.,

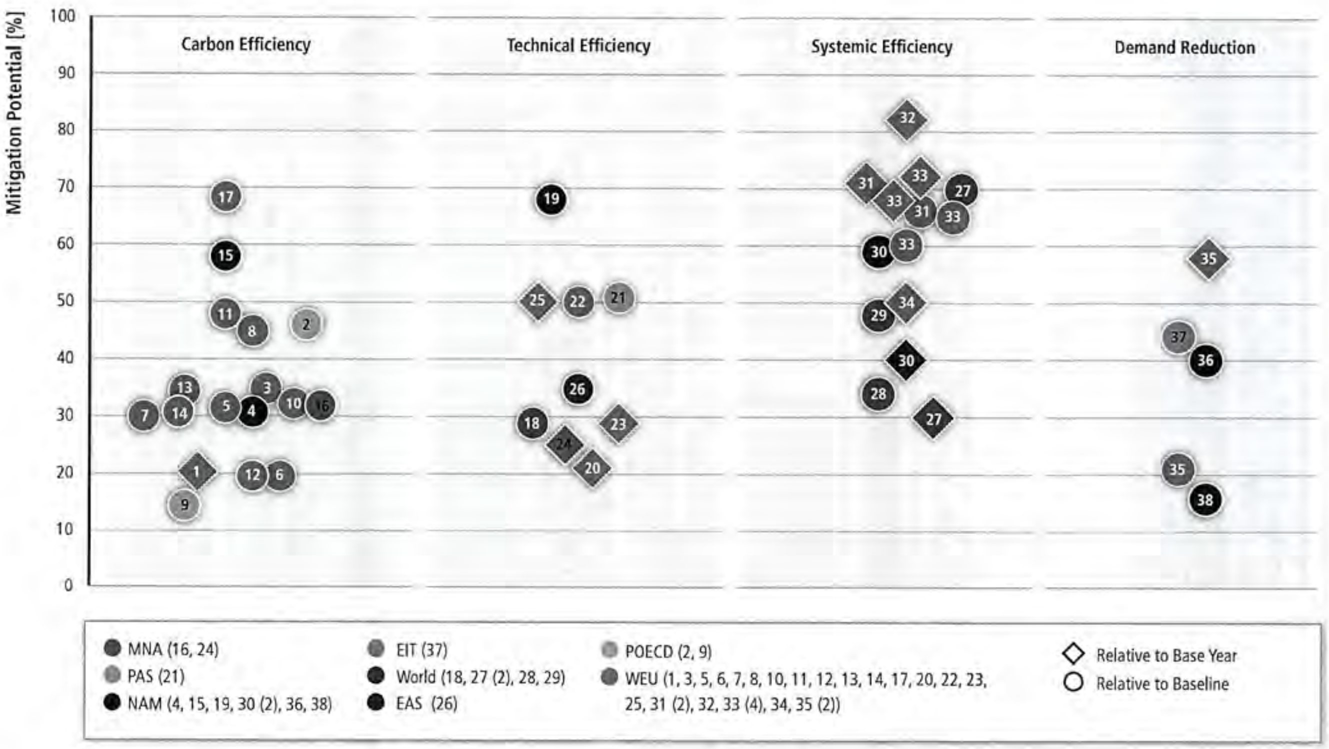


Figure 9.13 | Regional studies on aggregated mitigation potentials grouped by key identity (i.e., main mitigation strategy). Note: Values correspond to the percentage reduction as compared to baseline (circle), if available, otherwise to base year (diamond), studies are numbered, for details see Table 9.6, note that for some studies there are multiple entries (indicated by number in extra bracket). For RC10 region definitions see Annex II.2.1.

Table 9.6 | Summary of literature on aggregated mitigation potentials in buildings categorized by key mitigation strategies.[1]

Region (Study)[2]	Description of mitigation measures/package (year)[3]	End-uses[4]	Type[5]	Sector[6]	Base-end yrs	% change to baseline	% change to base yr[7]
CARBON EFFICIENCY							
EU (1)	Additional solar domestic hot water system	HW	T	RS	2010–20		20 %, pr.e
AU (2), AT (3) CA (4), DK (5) FL (6), DE (7) IT (8), JP (9) NL (10), ES (11) SE (12), CH (13) UK (14), US (15)	Solar electricity generation through buildings' roof-top PV installations	EL	T	BS	yearly	−46 %, −35 %, −31 %, −32 %, −19 %, −30 %, −45 %, −15 %, −32 %, −48 %, −20 %, −35 %, −31 %, −58 %	
IL (16)	All available rooftops are accounted for producing solar energy	EL	T	BS	yearly	−32 %	
ES (17)	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 %	
TECHNICAL EFFICIENCY							
World (18)	Significant efforts to fully exploit the potential for EE, all cost-effective renewable energy sources (RES) for heat and electricity generation, production of bio fuels, EE equipment	ALL	T	BS	2007–50	−29 %	
US (19)	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 %	
NO (20)	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 %
TH (21)	Building energy code and building energy labeling are widely implemented, the requirements towards (nearly) zero-energy building (NZEBs) are gradually strengthened by 2030	ALL	T	CS	by 2030	−51 %	
Northern Europe (22)	Improvements in lamp, ballast, luminaire technology, use of task/ambient lighting, reduction of illuminance levels, switch-on time, manual dimming, switch-off occupancy sensors, daylighting	L	T	CS	2011	−50 %	
Catalonia, ES (23)	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 %
BH (24)	Implementation of the envelope codes requiring that the building envelope is well-insulated and efficient glazing is used	C	T	CS	1 year		−25 %
UK (25)	Fabric improvements, heating, ventilation and air-conditioning (HVAC) changes (including ventilation heat recovery), lighting and appliance improvements and renewable energy generation	ALL	T	CS	2005–30		−50 % (CO_2)
CN (26)	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 %	
SYSTEMIC EFFICIENCY							
World (27)	Today's cost-effective best practice integrated design & retrofit becomes a standard	H/C	T-E	BS	2005–50	−70 %	−30 %
World (28)	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 %	
World (29)	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 %	
US (30)	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 %
EU27 (31)	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 %
DK (32)	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 %

Region (Study)[2]	Description of mitigation measures/package (year)[3]	End-uses[4]	Type[5]	Sector[6]	Base-end yrs	% change to baseline	% change to base yr[7]
CH (33)	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 %
	Buildings comply with zero energy standard (no heating demand)	H/W	T	RS	2000–50	−65 %	−72 %
DE (34)	The proportion of very high-energy performance dwellings increases by up to 30 % of the total stock in 2020; the share of (nearly) zero-energy buildings (NZEBs) makes up 6 %	H/W	T	BS	2010–20		−25 %(pr.e) −50 % (CO_2)
ENERGY SERVICE DEMAND REDUCTION							
FR (35)	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	−21 %	−58 %
US (36)	Influence of five lifestyle factors reflecting consumers' behavioural patterns on residential electricity consumption was analyzed	EL	T	RS	2005	−40 %	
LT (37)	Change in lifestyle towards saving energy and reducing waste	ALL	T	RS	1 year	−44 %	
US (38)	Commissioning as energy saving measure applied in 643 commercial buildings	ALL	T	CS	1 year	−16 % (existing buildings) −13 % (new buildings)	

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) 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 et al. (2008a), 21: Sartori et al. (2009), 22: Pantong et al. (2011), 23: Dubois and Blomsterberg (2011), 24: Garrido-Soriano et al. (2012), 25: Radhi (2009), 26: Taylor et al. (2010), 27: Zhou et al. (2011a), 28: Ürge-Vorsatz et al. (2012c), 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 (2011).
3) EE – energy efficiency;
4) H – space heating; C – space cooling; W – hot water; L – lighting; APPL – appliances; ALL – all end-uses; El - elecriticy;
5) T – technical; T-E – techno-economical;
6) BS – the whole building sector; RS – residential sector; CS – commercial sector;
7) pr.e. – primary energy.

2012). Figure 9.13 and the corresponding Table 9.6 synthesize 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 organized by the four key identities discussed 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 categorizations 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.

The efficiency and cost studies presented here represent a single snapshot in time, 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 (NAS) study (NAS, 2010) of the energy savings potentials of energy efficiency technologies and programmes across all sectors in the United States note that "[s]tudies 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).

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, and for each of which several mitigation alternatives exist, giving a comprehensive account of costs and potentials of each, or even many, is out of the scope of this report. The next two sections focus on selected *key* mitigation options and discuss their costs and potentials in more depth. Section 9.6.2 focuses on whole-building approaches for new and retrofitted buildings, while the Section 9.6.3 analyzes a selection of important technologies systematically. Finally, Section 9.6.5 discusses the sensitivity of the findings from the earlier section 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 et al., 2012a; 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 (Kats, 2009). For commercial buildings, there are instances where these methods have found no additional cost in meeting standards as high as the Passive House standard (see Section 9.3; Lang Consulting, 2013), or where the cost

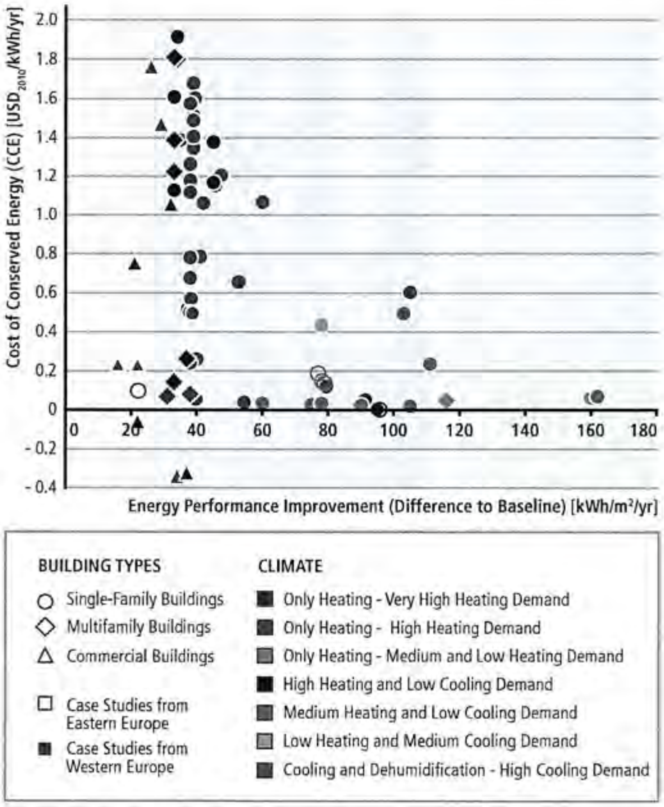


Figure 9.14 | Cost of conserved energy as a function of energy performance improvement (kWh/m^2/yr difference to baseline) to reach 'Passive House' or more stringent performance levels, for new construction by different building types and climate zones in Europe. A discount rate of 3 % and the lifetime of 30 years for retrofit and 40 years for new buildings have been assumed. Sources: Hermelink (2006), Galvin (2010), ETK (2011), Gardiner and Theobald (2011), Nieminen (2011), Energy Institute Vorarlberg (2013), PHI (2013), Harvey (2013).

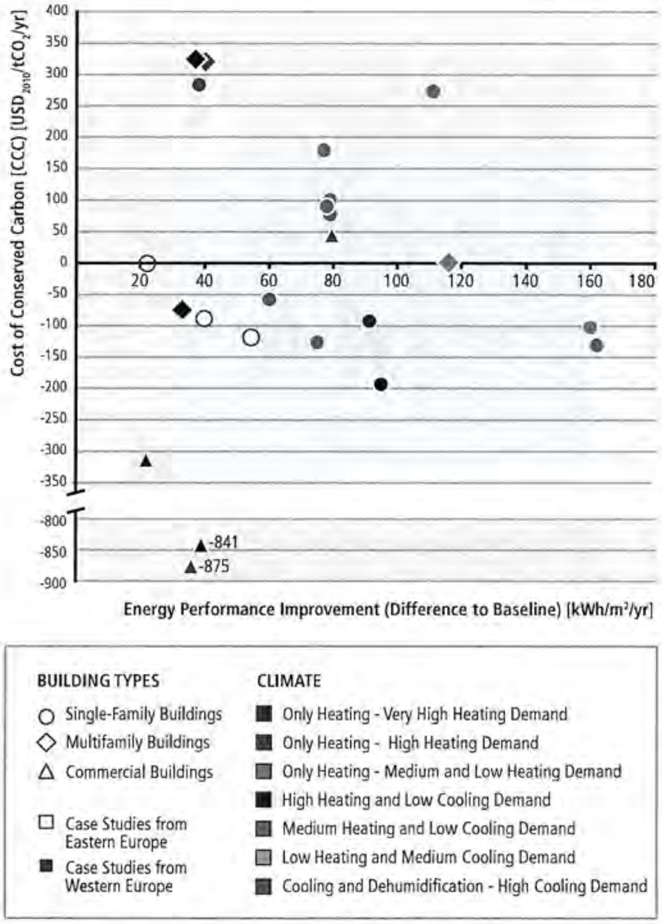


Figure 9.15 | Cost of conserved carbon as a function of specific energy consumption for selected best practices shown in Figure 9.14. A discount rate of 3 % and the lifetime of 30 years for retrofit and 40 years for new buildings have been assumed. Sources: Hermelink (2006), Galvin (2010), ETK (2011), Gardiner and Theobald (2011), Nieminen (2011), Energy Institute Vorarlberg (2013), PHI (2013), Harvey (2013).

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 a 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 irrespective of performance features (Davis Langdon, 2007; Urban Green Council and Davis Langdon, 2009). Collectively, these studies, along with evidence in 9.3 and the tables in this section indicate that 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 9.3.5 highlights selected published estimates of the incremental cost of net zero-energy buildings; even for these buildings, there are cases where there appears to have been little additional cost (e.g., NREL Laboratory). The costs of new 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 payback 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 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 optimized with regard to the

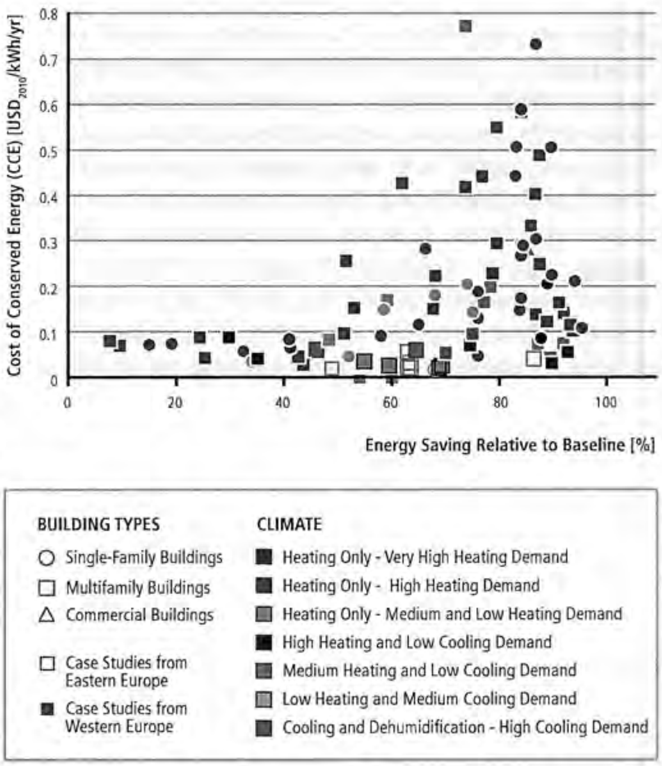


Figure 9.16 | Cost of conserved energy as a function of energy saving in percent for European retrofitted buildings by building type and climate zones. A discount rate of 3 % and the lifetime of 30 years for retrofit and 40 years for new buildings have been assumed. Sources: Hermelink (2006), Galvin (2010), ETK (2011), Gardiner and Theobald (2011), Nieminen (2011), Energy Institute Vorarlberg (2013), PHI (2013), Harvey (2013).

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 Section 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). Figure 9.14 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, which extends from three-digit negative costs to triple digit positive costs per ton of CO_2 emissions avoided.

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, especially 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 retrofits—i.e., their cost-effectiveness can remain at 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 in previous sections depend heavily on various factors and significantly influence the cost-effectiveness of the investments. While these investments vary with the types of measures, a few common factors can be identified.

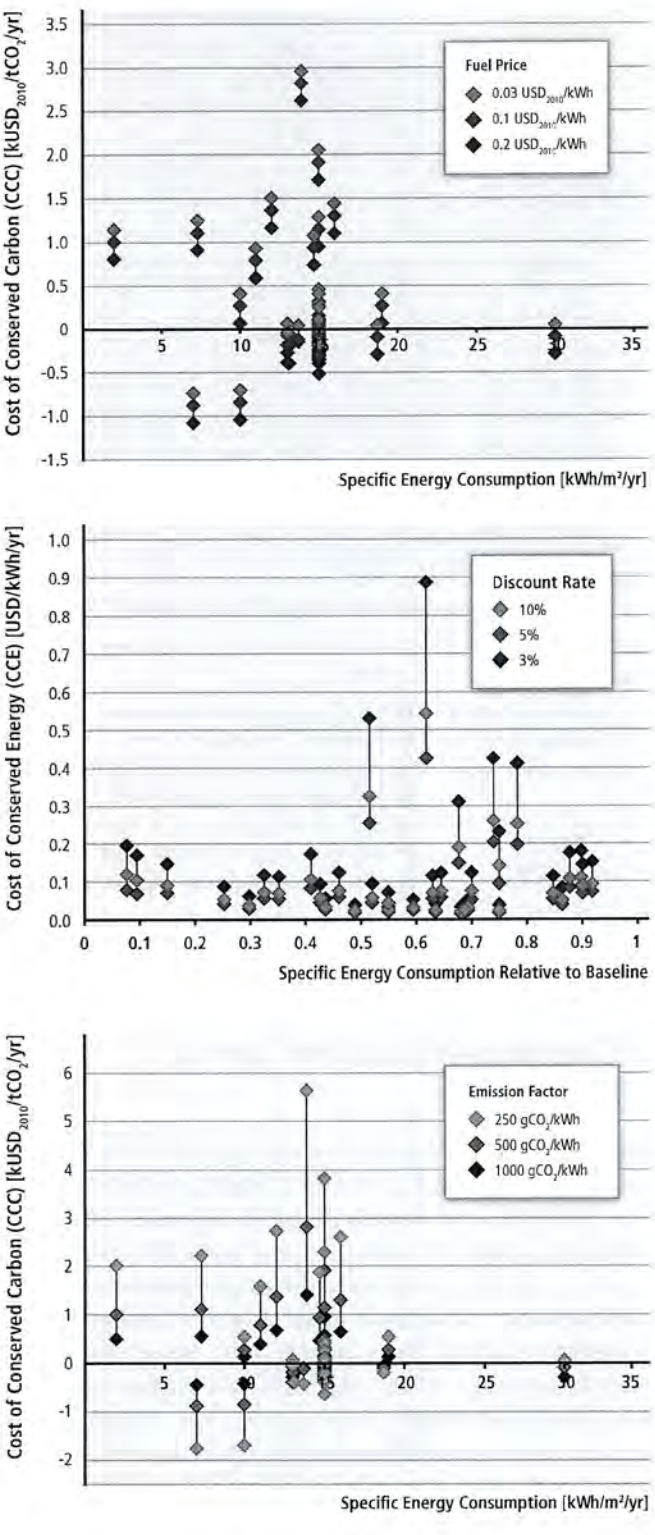


Figure 9.17 | Sensitivity analysis of the key parameters: Top: CCC for new buildings in response to the variation in fuel price; middle: CCE for retrofit buildings in response to the variation in discount rate for selected data points shown in Figure 9.14, Figure 9.15 and Figure 9.16; bottom: CCC for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

For the cost-effectiveness of energy-saving investments, the state of efficiency of the baseline is perhaps the most important determining factor. For instance, a Passive House represents a factor of 10–20 improvement when compared to average building stocks, but only a fraction of this when compared to, for instance, upcoming German new building codes. Figure 9.16 and Figure 9.17 both vary the baseline for the respective measure.

CCE figures and thus 'profitability', fundamentally depend on the discount rate and assumed lifetime of the measure, and CCC 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.

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.[1] 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 relevant 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) and GEA (2012), synthesizing previous research efforts (Mills and Rosenfeld, 1996), recognize the following five major categories of co-benefits attributed to mitigation actions in buildings: (1) health effects (e.g., reduced mortality and morbidity from improved indoor and outdoor air quality), (2) ecological effects (e.g., reduced impacts on ecosystems due to the improved outdoor environment), (3) economic effects (e.g., decreased energy bill payments, employment creation, improved energy security, improved productivity), (4) service provision benefits (e.g., reduction of energy losses during energy transmission and distribution), and (5) 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 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 focuses on selected co-benefits/risks, with a view to providing methods, quantitative information, and examples that can be utilized in the decision-making process.

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., 2010; Carley et al., 2011; Gülen, 2011). A review of the literature on quantification of employment effects of energy efficiency and mitigation measures in the building sector is summarized in Figure 9.18. The bulk of the studies reviewed, which mainly concern developed economies, point out that the implementation of mitigation interventions in buildings generates on average 13 (range of 0.7 to 35.5) job-years per million USD_{2010} 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 million USD_{2010} 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,

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[1] 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 et al. (2010b)
↑ Enhanced asset values of buildings	X	X	X	X	X	X		X		Miller et al. (2008); Brounen and Kok (2011); Deng et al. (2012b)
↑ 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		Tirado Herrero et al. (2012b); Healy (2004); Liddell and Morris (2010); Hills (2011); Ürge-Vorsatz and Tirado Herrero (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
↑ 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 et al. (2012a)
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 et al. (2010b); Howden-Chapman and Chapman (2012); Milner et al. (2012)
↑ *fuel poverty alleviation*	X		X	X	X		X	X		Tirado Herrero et al. (2012b); Healy (2004); Liddell and Morris (2010); Hills (2011); Ürge-Vorsatz and Tirado Herrero (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 et al. (2012b); see Sections 9.5 and 12.8

to what extent investing in 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 or not inside 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).

9.7.2.2 Energy security

Implementation of 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: (1) 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); (2) reducing cooling-related peak power demand and shifting demand to off-peak periods (Borg and Kelly, 2011; Steinfeld et al., 2011); and (3) 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 et al., 2010b). On average, energy efficient buildings may result in increased productivity by 1–9 % or even higher for specific activities or case studies. The productivity gains can be attributed to: (1) reduced working days lost due to asthma and respiratory allergies; (2) fewer work hours affected by flu, respiratory illnesses, depression, and stress; and (3) improved worker performance from changes in thermal comfort and lighting. Productivity gains can rank among the highest value co-benefits when these are monetized, especially in countries with high labour 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. The rebound effect 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 et al., 2012b)

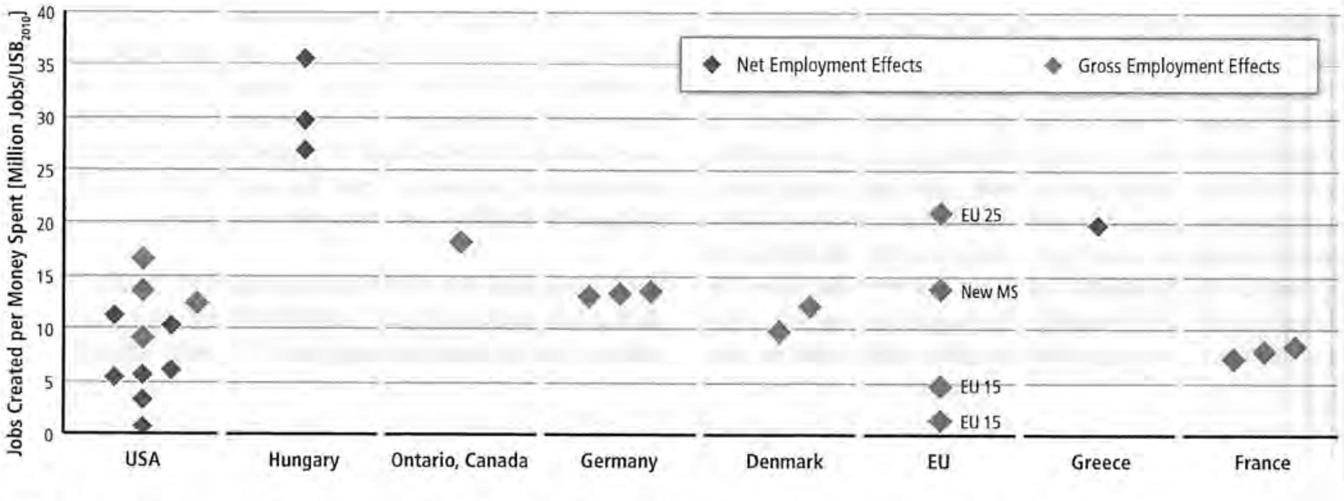

Figure 9.18 | Employment effects attributed to GHG mitigation initiatives from different provinces, countries and regions in the building sector.

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 USA, 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).

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 (Hens et al., 2009; Roy, 2000), implying that rebound contributes positively to energy service affordability and development. 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 industrialization (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 Tirado Herrero, 2012). 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 the elderly (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; Ürge-Vorsatz and Tirado Herrero, 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: (1) reduction of indoor air pollution, (2) improvement of indoor environmental conditions, and (3) alleviation of fuel poverty 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 cook fuel's contribution to outdoor air pollution, making a total of about 4 million (see WGII Chapter 11.9.1.3). Several climate mitigation options such as improved cookstoves, switching to cleaner fuels, changing behaviours, and switching to more efficient and less dangerous lighting technologies 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 programme 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).

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

Table 9.8 | Healthy years gained per thousand USD_{2010} 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	1.30—1.79	0.66—1.19	~1.2	0.70—0.76	1.70—2.97	0.55—9.30
Access to cleaner fuels: Kerosene	11.1—15.4	1.46—8.77	~9.7	5.07—5.56	14.8—25.8	4.11—79.5
Improved stoves	36.7—45.9	0.84—0.98	2.03—2.52	n.a.	62.4—70.7	1.58—3.11

well as reduced sick building syndrome (SBS) symptoms (Fisk, 2002; Singh et al., 2010b). On the other hand, insufficient ventilation in airtight buildings has been 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). In countries such as Poland, Germany, or Spain, this 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 et al., 2012; Tirado Herrero et al., 2012b). Improved residential insulation is expected to reduce illnesses associated with room temperature thus provide 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 for each USD_{2010} 1 invested for warming homes reduces the healthcare costs by USD_{2010} 0.49 (Liddell, 2008). Such findings suggest that 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 mitigation measures in the building sector reduces the consumption of fossil fuels and electricity, thus improving the outdoor air quality and resulting in: (1) reduced mortality and morbidity, particularly in developing countries and big cities (Smith et al., 2010; Harlan and Ruddell, 2011; see Section 12.8); and (2) less stresses on natural and anthropogenic ecosystems (see Section 7.9.1). Quantification and valuation of these benefits is possible, and allows them to be integrated into cost-benefit analysis. Many studies (Levy et al., 2003; Aunan et al., 2004; Mirasgedis et al., 2004; Chen et al., 2007; Crawford-Brown et al., 2012) have monetized the health and environmental benefits attributed to reduced outdoor air pollution that result from 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 USD_{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 USD_{2010}/tCO_2 in EU, 7 USD_{2010}/tCO_2 in China and 46 USD_{2010}/tCO_2 in India, accounting for only the mortality impacts associated with $PM_{2.5}$ emissions. Please refer to Section 5.7 for other estimates in the assessed literature.

9.7.3.3 Other environmental benefits

Energy efficiency measures that are implemented in buildings result 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 façades/walls in buildings, results in: (1) reducing heat gains for buildings in hot climates; (2) reducing the heat island effect; (3) improving air quality; (4) enhancing urban biodiversity, especially with the selection of indigenous vegetation species; (5) absorbing CO_2 emissions, etc. (see Cam, 2012; Xu et al., 2012b; Gill et al., 2007; and Section 12.5.2.2).

9.8 Barriers and opportunities

Strong barriers—many 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 the options to overcome them, such as policies, measures, and innovative financing schemes. A vast literature on barriers and opportunities in buildings enumerates and describes these factors (Brown et al., 2008b; Ürge-Vorsatz et al., 2012a; Power, 2008; Lomas, 2009; Mlecnik, 2010; Short, 2007; Hegner, 2010; Stevenson, 2009; Pellegrini-Masini and Leishman, 2011; Greden, 2006; Collins, 2007; Houghton, 2011; Kwok, 2010; Amundsen, 2010; Monni, 2008).

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, financing, qualified personnel, economic informality, and generally insufficient service levels lead to suboptimal policies and measures thus 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).

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 modelling 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 (1) a statistical analysis of a large population of scenarios from integrated models (665 scenarios in total) grouped by their long-term CO_2-equivalent (CO_2eq) 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 (2) a more detailed analysis of a small selection of integrated and end-use/sectoral models. The source of the integrated models is the WGIII AR5 Scenario Database (see Section 6.2.2 for details), and those of the sectoral models are Cornelissen et al. (2012), Deng et al. (2012a), Dowling et al. (2012), GPI (2010), Harvey (2010), IEA (2012c0a), Laustsen (2010), McNeil et al. (2013), Ürge-Vorsatz et al. (2012a3), WBCSD (2009), WEO (2011).

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 possibly triple by mid-century. While the median of integrated model scenarios forecast an approximate 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 the Global Change Assessment Model (GCAM), all of which project 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.

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 stabilization, whereas the vast majority of ambitious scenarios from the bottom-up/sectoral literature stabilize or even decline despite the increases in wealth, floorspace, service levels, and amenities (see Section 9.2). Several stringent mitigation scenarios from integrated mod-

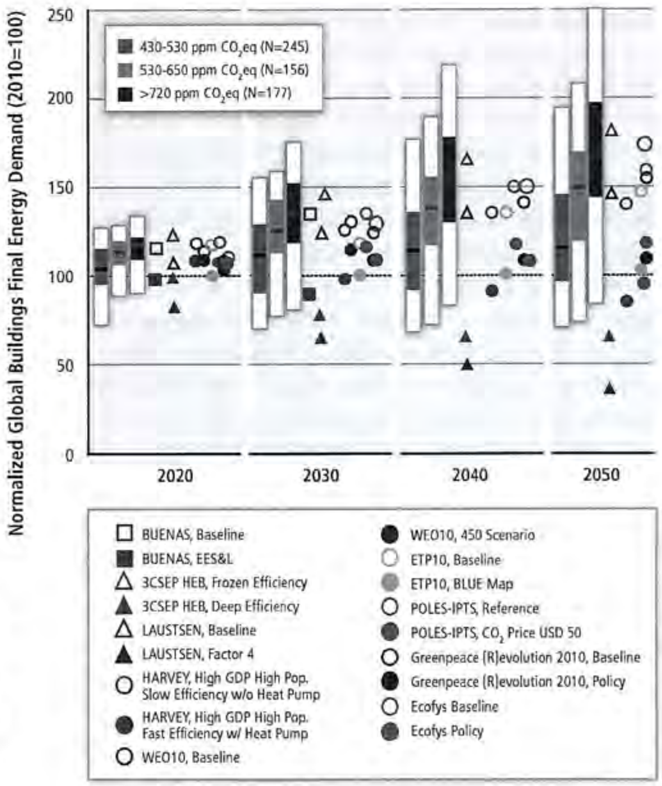

Figure 9.19 | Development of normalized annual global building final energy demand (2010=100) until 2050 in the integrated modelling literature, grouped by the three levels of long-term CO_2eq concentration level by 2100 (245 scenarios with 430–530 ppm CO_2eq, 156 scenarios with 530–650 ppm CO_2eq, and 177 scenarios exceeding 720 ppm CO_2eq—for category descriptions see Chapter 6.3.3; see box plots) and sectoral/bottom-up literature (9 baseline scenarios and 9 advanced scenarios; see square, triangle and circle symbols). Sectoral scenarios covering appliances (A) only are denoted as squares (■), scenarios covering heating/cooling/water heating (HCW) as triangles (▲), scenarios covering heating/cooling/water heating/lighting/appliances (HCWLA) as circles (●). Filled symbols are for baseline scenario, whereas empty symbols are for advanced scenarios. Box plots show minimum, 25th percentile, median, 75th percentile and maximum. Sources: Cornelissen et al. (2012), Deng et al. (2012a), Dowling et al. (2012), GPI (2010), Harvey (2010), IEA (2012c0a), Laustsen (2010), McNeil et al. (2013), Ürge-Vorsatz et al. (2012a3), WBCSD (2009), WEO (2011) and WG III AR5 Scenario Database (Annex II.10).

Note on this section: This section builds upon emissions scenarios, which were collated by Chapter 6 in the WGIII 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 CO2eq, 480–530 ppm CO2eq, 530–580 ppm CO2eq, 580–650 ppm CO2eq, 650–720 ppm CO2eq, and > 720 ppm CO2eq 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 ppm CO2eq—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 CO2eq 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).

els 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.

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 is 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 et al. (2012d) show 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.

The trends noted above 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 stabilize 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

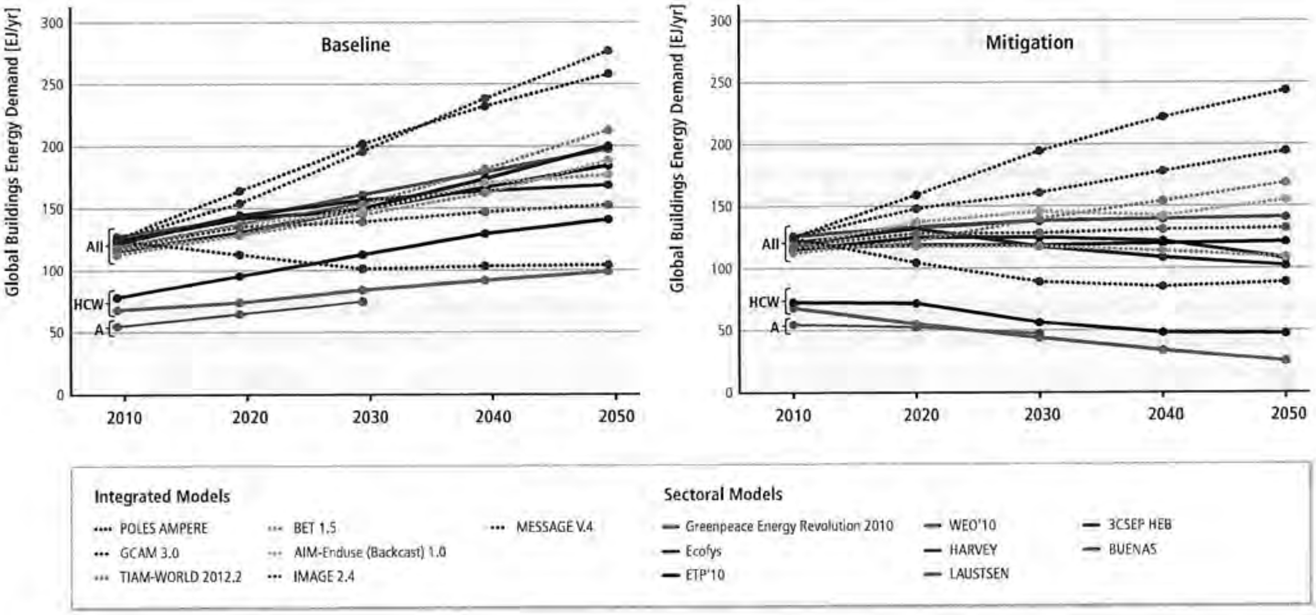

Figure 9.20 | Annual global final energy demand development in the building sector by 2050 (except WEO'10 and BUENAS) in selected sectoral models for baseline (left) and advanced (right) scenarios, for total energy (All, heating/cooling/hot water/lighting/appliances), thermal energy (HCW, includes heating/cooling/hot water), and appliances (A); compared to selected integrated models. Dashed lines show integrated models, solid lines show sectoral/bottom-up models. Sources: Cornelissen et al. (2012), Deng et al. (2012a), Dowling et al. (2012), GPI (2010), Harvey (2010), IEA (2012c0a), Laustsen (2010), McNeil et al. (2013), Ürge-Vorsatz et al. (2012a3), WBCSD (2009), WEO (2011) and WG III AR5 Scenario Database (Annex II.10).

Note: 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 WGIII AR5 scenario database and their 450 ppm 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'10 Current 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.

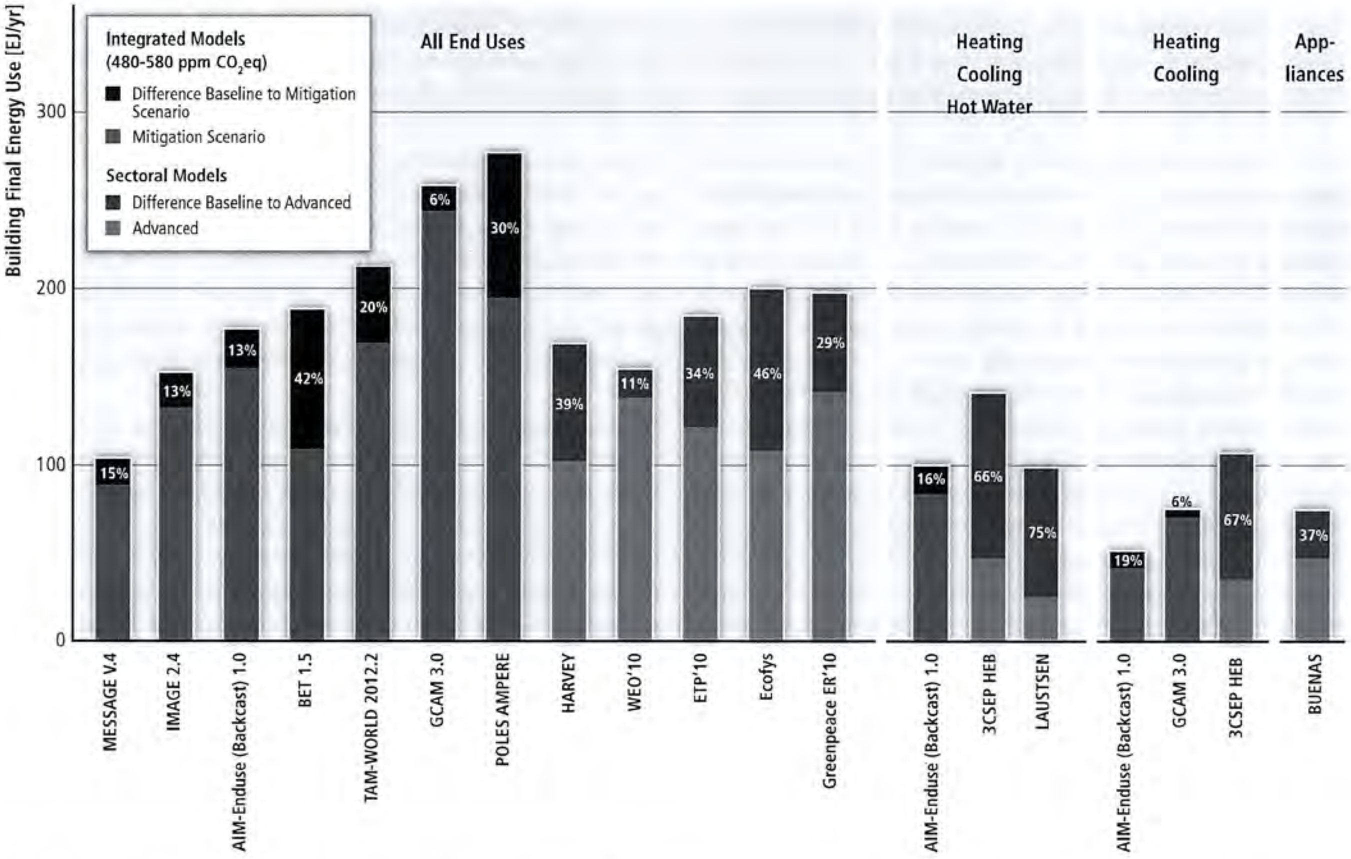

Figure 9.21 | Building final energy use in EJ/yr in 2050 (2030 for BUENAS and WEO'10) for advanced scenarios, modelling four groups of building end-uses as compared to reference ones. Blue bars show scenarios from integrated models meeting 480–580 ppm CO_2eq concentration in 2100, orange/red bars are from sectoral models. Sources: Cornelissen et al. (2012), Deng et al. (2012a), Dowling et al. (2012), GPI (2010), Harvey (2010), IEA (2012c0a), Laustsen (2010), McNeil et al. (2013), Ürge-Vorsatz et al. (2012a3), WBCSD (2009), WEO (2011) and WG III AR5 Scenario Database (Annex II.10)

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.

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 suggests 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 decarbonization. In general, 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 (see Section 6.8)—except for a small selection of studies.

Fuel switching to electricity that is increasingly being decarbonized is a robust mitigation strategy as shown in Sections 6.3.4 and 6.8. However, as Figure 9.23a 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., the use of more electricity as a share of building energy supply 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.

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 dif-

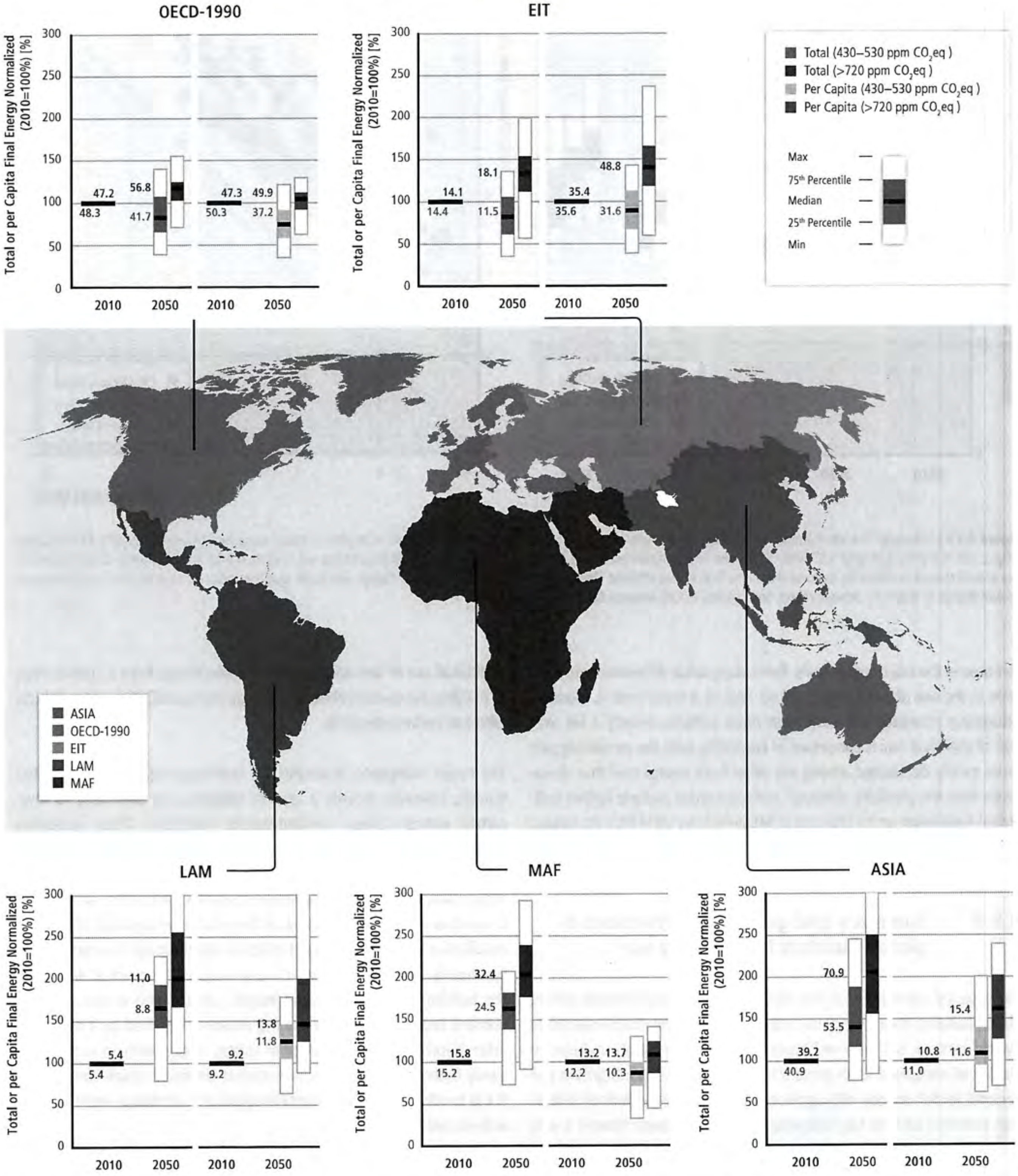

Figure 9.22 | Normalized total (for first two pairs of box plots) and per capita (for next two pairs of box plots) buildings final energy demand in 2010 and 2050 for each of the RC5 regions (Annex II.2.2) in scenarios from integrated models (2010=100). The absolute values of the medians are also shown 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 CO_2eq and 154 scenarios exceeding 720 ppm CO_2eq—for category descriptions see Section 6.3.2). Note that the 2010 absolute values are not equal for the two CO_2eq concentration categories because for most integrated models 2010 is a modelling year implying some variation across models, such as in the treatment of traditional biomass. Sources: WG III AR5 Scenario Database (Annex II.10).

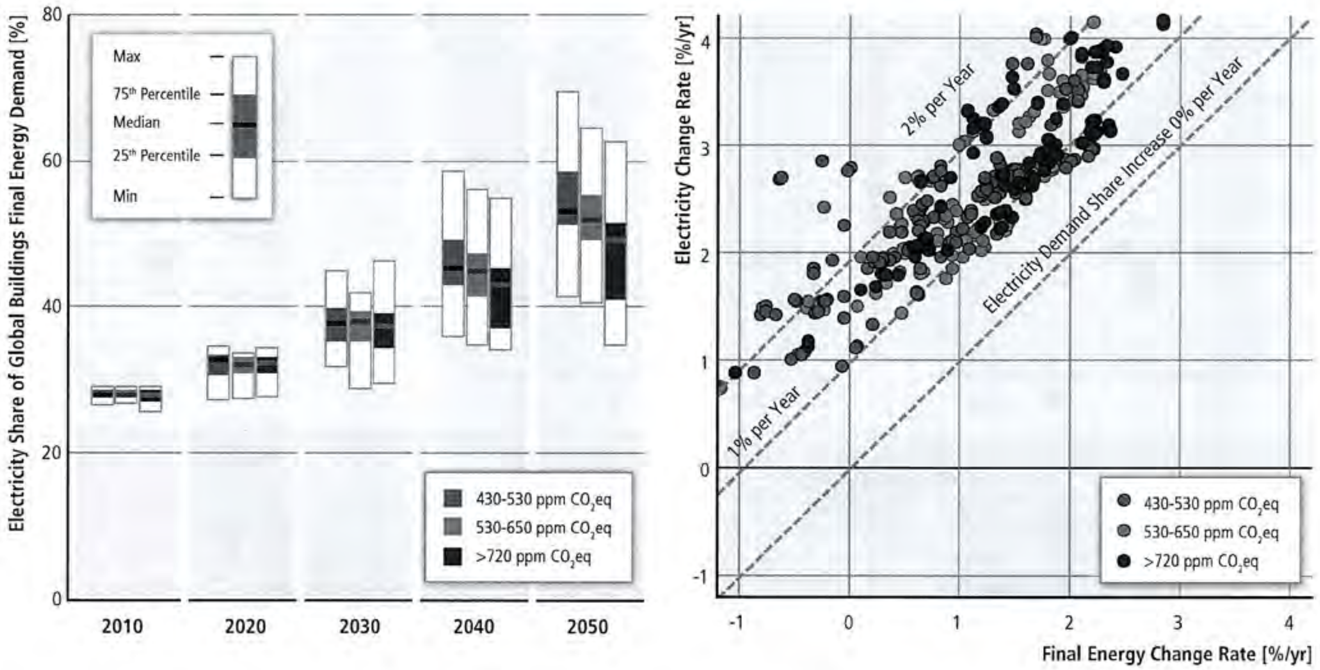

Figure 9.23 | Left panel: The development in the share of electricity in global final energy demand until 2050 in integrated model scenarios (167 scenarios with 430–530 ppm CO_2eq, 138 scenarios with ppm 530–650 CO_2eq, and 149 scenarios exceeding 720 ppm CO_2eq—for category descriptions see Chapter 6.3.3), and right panel 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: WG III AR5 Scenario Database (Annex II.10).

ferences 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.

9.9.4 Summary and general observations of global building final energy use

The material summarized in this section concludes that without action, global building final energy use may double or potentially even triple by mid-century, but with ambitious action it can possibly stabilize or decline as compared to its present levels. 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 significantly reduce demand for both primary fuels and electricity 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 can be 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 integrated models, however, include a greater emphasis on switching to low-carbon energy carriers (predominantly electricity). These strategies place 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 carbon dioxide capture and storage (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 (see Section 6.8).

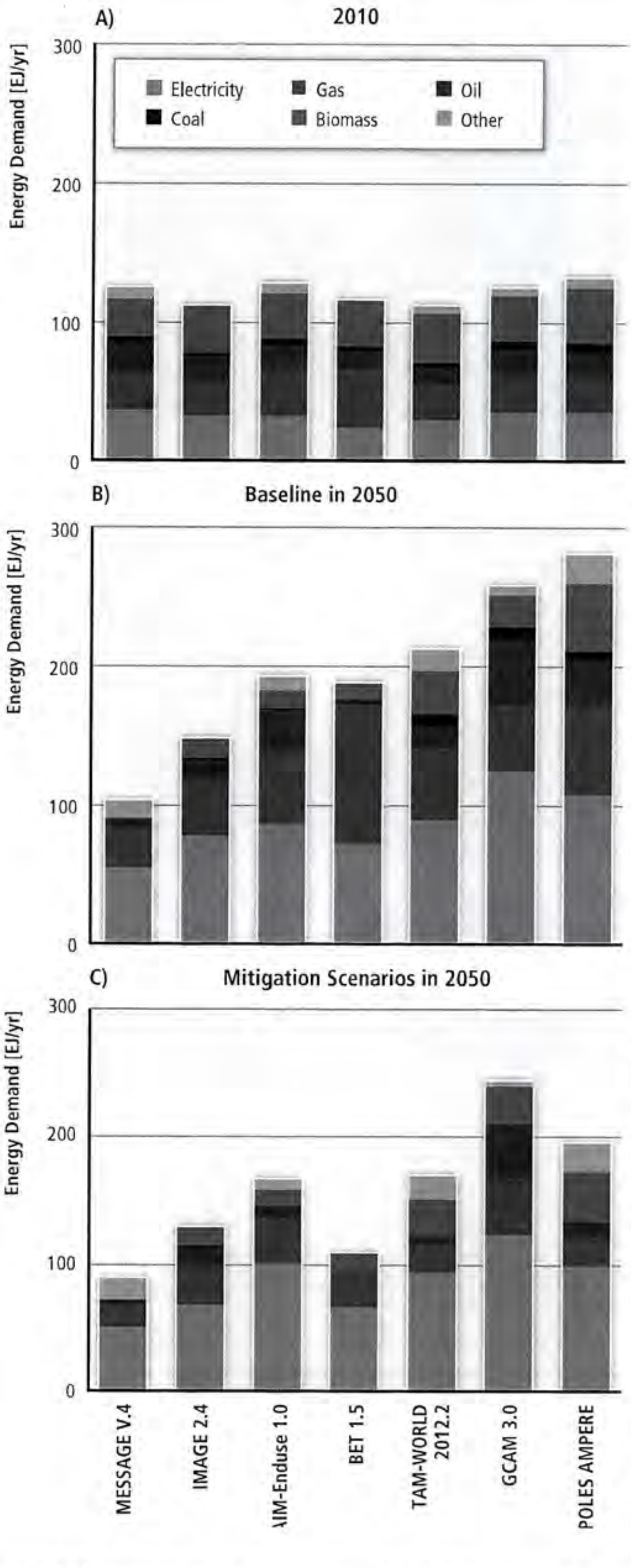

Figure 9.24 | Global buildings final energy demands by fuel for the seven baseline scenarios of seven integrated models and their corresponding mitigation scenarios (480–580 ppm CO_2eq concentration in 2100). AIM-Enduse 1.0 = AIM-Enduse (Backcast) 1.0. Sources: WG III AR5 Scenario Database (Annex II.10).

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

Section 9.8 shows 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 that show reductions of emissions at low and negative costs; many of them have been implemented in developed countries and, more recently, in developing countries. When these policies are implemented in a coordinated manner, they can be effective in reversing the trend of growing energy consumption. This chapter shows that 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, policymakers have recently focused on the need to change 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 that specifically target the existing stock, e.g., aiming at accelerating rates of energy refurbishment and avoiding lock-in to suboptimal retrofits—for example, 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 summarized 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: (1) *Regulatory measures* are one of the most effective and cost-effective instruments, for example, building codes and appliance standards (Boza-Kiss et al., 2013) if properly enforced (Weiss et al., 2012); see also (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. (2) *Information instruments* including equipment energy labels, building labels and certificates, and mandatory energy audits can be

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-Kiss et 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, USD_{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 $MtCO_2$ (2010–2011) LV: 0.002 $MtCO_2$/yr in 2016 (estimated in 2008) ES: 0.35 $MtCO_2$/yr in 2012 UK : 0.02 $MtCO_2$/yr by 2020 (estimated in 2011)	EU region: < 36.5 USD_{2010}/tCO_2 ES: 0.17 USD_{2010}/tCO_2 LV: −206 USD_{2010}/tCO_2	[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 $MtCO_2$/yr in 2025 (Top Runner Scheme, 2007) US: 158 $MtCO_2$ cumulative in 2030 (2010), updating the standard—18 $MtCO_2$/yr in 2040 (2010) KE: 0.3 $MtCO_2$/yr (for lighting only) BF: 0.01 $MtCO_2$/yr (lighting only)	JP: 51 USD_{2010}/tCO_2 (Top Runner) Mor: 13 USD_{2010}/tCO_2 AU: −52 USD_{2010}/tCO_2 US: −82 USD_{2010}/tCO_2 EU: −245 USD_{2010}/tCO_2	[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 endorsement labelling (e.g., Energy Star) and mandatory energy labelling (e.g., the EU energy label). Technical specifications for the label should be regularly updated to adjust to the best products on the market. MEPS and labels are usually co-ordinated policy measures with common technical analysis.	EU: 237 $MtCO_2$ (1995–2020) OECD N-Am: 792 $MtCO_2$ (1990–2010) OECD EU: 211 $MtCO_2$ (1990–2010) NL: 0.11 $MtCO_2$/yr (1995–2004) DK: 0.03 $MtCO_2$/yr (2004)	AU: −38 USD_{2010}/tCO_2	[9,10,11]
Building labels and certificates rate buildings related to their energy performance and provide credible information about it to users/buyers.	Building labels could be mandatory (for example in the EU) or voluntary (such as BREEAM, CASBEE, Effinergie, LEED, European GreenBuilding label, Minergie and PassivHaus). Labels are beginning to influence market prices (Brounen and Kok, 2011).	SK: 0.05 $MtCO_2$ (during 2008–2010) for mandatory certification SK: 0.001 $MtCO_2$ (during 2008–2010) for promoting voluntary certification and audits	EU: 27 USD_{2010}/tCO_2 (2008–2010) for mandatory certification DK: almost 0 USD_{2010}/tCO_2	[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 $MtCO_2$ (during 2008–2010) for promoting voluntary certification and audits FI: 0.036 $MtCO_2$ (2010)	FI: 27.7 USD_{2010}/tCO_2 (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 $MtCO_2$ (introduction of sustainable procurement principle) (2011–2013) CN: 3.7 $MtCO_2$ (1993–2003) MX: 0.002 $MtCO_2$ (2004–2005) UK: 0.34 $MtCO_2$ (2011) AT: 0.02 $MtCO_2$ (2010)	SK: 0.03 USD_{2010}/tCO_2 CN: −10 USD_{2010}/tCO_2	[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:40–55$MtCO_2$ by 2010 AT: 0.016 $MtCO_2$/yr in 2008–2010 US: 3.2 $MtCO_2$/yr CN: 34 $MtCO_2$	EU: mostly at no cost AT: no cost HU: < 1 USD_{2010}/tCO_2 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 et al., 2010b).	FR: 6.6 $MtCO_2$/yr (2006–2009) IT: 21.5 $MtCO_2$ (2005–2008) UK: 24.2 $MtCO_2$/yr (2002–2008) DK: 0.5 $MtCO_2$/yr (2006–2008) Flanders (BE): 0.15 $MtCO_2$ (2008–2016)	FR: 36 USD_{2010}/tCO_2 IT: 12 USD_{2010}/tCO_2 UK: 24 USD_{2010}/tCO_2 DK: 66 USD_{2010}/tCO_2 Flanders (BE): 201 USD_{2010}/tCO_2	[19, 20, 21, 22, 23, 24, 25, 26, 27]
Carbon markets limit the total amount of allowed emissions. Carbon emission allowances are then distributed and traded.	Carbon cap and trade for the building sector is an emerging policy instrument (e.g., the Tokyo 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 $MtCO_2$ (average cumulative saving per project for 32 registered CDM projects on residential building efficiency, 2004–2012) JI: 699 $MtCO_2$ (cumulative) from the single JI project on residential building energy efficiency (2006–2012)	CDM end-use energy efficiency projects, In:– 113 to 96 USD_{2010}/tCO_2 JI projects (buildings): between 122 and 238 USD_{2010}/tCO_2	[28, 29, 30]

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, USD_{2010}/tCO_2 per yr)	References
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 $MtCO_2$/yr (2006) DE: 24 $MtCO_2$ cummulative (1999–2010) DK: 2.3 $MtCO_2$ (2005) NL: 3.7–4.85 $MtCO_2$/yr (1996–2020)	SE: 8.5 USD_{2010}/tCO_2 DE: 96 USD_{2010}/tCO_2 NL: −421 to −552 USD_{2010}/tCO_2 (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 $MtCO_2$ (2006–2009) IT: 0.65 $MtCO_2$ (2006–2010) FR: 1 $MtCO_2$ (2002) US: 88 $MtCO_2$ (2006)	TH: 26.5 USD_{2010}/tCO_2	[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 $MtCO_2$ cummulative (1993–2003) UK: 1.41 $MtCO_2$ (2008–2009) CZ: 0.05 $MtCO_2$ (2007) AU: 0.7 $MtCO_2$ (2009–2011) FR: 0.4 $MtCO_2$ (2002–2006)	DK: 0.5 USD_{2010}/tCO_2 UK: 84.8 USD_{2010}/tCO_2 FR: 17.9 USD_{2010}/tCO_2	[35, 37, 38, 39]
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 $MtCO_2$ (2008–2009) LT: 0.33 $MtCO_2$/yr (2009–2020) PL: 0.98 $MtCO_2$ (2007–2010)	TH: 108 USD_{2010}/tCO_2 (total cost of loan)	[37, 40]
Voluntary and negotiated agreements are tailored contracts between an authority and another entity, aimed at meeting a predefined level of energy savings.	Voluntary programmes can be also applied in the built environment as in the Netherlands and Finland, where housing association and public property owners agree on energy efficiency targets with the government. 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 $MtCO_2$ NL: 2.5 $MtCO_2$ (2008–2020) DK: 0.09 $MtCO_2$/yr (1996)	FI: 0.15 USD_{2010}/tCO_2 NL: 14 USD_{2010}/tCO_2 DK: 39 USD_{2010}/tCO_2	[2, 13, 41, 42]
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 $MtCO_2$/yr (2005) UK: 0.01 $MtCO_2$/yr (2005) EU: 0.0004 $MtCO_2$ (2009) FI: 0.001 $MtCO_2$/yr (2010) UK: 0.25 % household energy saving/yr, that is 0.5 $MtCO_2$/yr (cumulated 2011–2020) (billing and metering)	BR: −69 USD_{2010}/tCO_2 UK: 8.4 USD_{2010}/tCO_2 EU: 40.2 USD_{2010}/tCO_2 US: 20–98 USD_{2010}/tCO_2	[2, 43, 44, 45, 46]
Public Leadership Programmes are public practices going beyond the minimum requirements in order to lead by example and demonstrate good examples.		IE: 0.033 $MtCO_2$ (2006–2010) BR: 6.5–12.2 $MtCO_2$/yr	ZA: 25 USD_{2010}/tCO_2 BR: −125 USD_{2010}/tCO_2	[2, 47]

Notes: Country codes (ISO 3166): AT-Austria; AU-Australia; BE- Belgium; BF- Burkina Faso; BR- Brazil; CN- China; CZ-Czech 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, 2003);[2] (Koeppel and Ürge-Vorsatz, 2007);[3](DECC, 2011); [4] (Government 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] (Government of Slovakia, 2011); [13] (Government of Finland, 2011); [14] (FI, 2005); [15] (Van Wie McGrory 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 et al., 2010b); [26] (Giraudet et al., 2011); [27] (Langham et al., 2010); [28] (BETMG, 2012); [29] (UNEP Risoe, 2012); [30] (Bertoldi et al., 2013b); [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] (Missaoui and Mourtada, 2010); [39] (Hayes et al., 2011); [40] (Galvin, 2012); [41] (Rezessy and Bertoldi, 2010); [42] (MIKR, 2011); [43] (Uitdenbogerd et al., 2009); [44] (CPI, 2011); [45] (UK DE, 2011); [46] (CB, 2012); [47] (Government of Ireland, 2011).

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). (3) *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). (4) *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 (UNEP SBCI, 2007). 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 overcome first cost barriers for deep retrofits (McGilligan et al., 2010). (5) *Voluntary agreements* include programmes such as industry agreements. Their effectiveness depends on the context and on accompanying policy measures (Bertoldi, 2011). (6) *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 successfully adopted building sector policies. The most popular instruments in developing countries so far have been appliance standards, public procurement, and leadership programmes. Table 9.9 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 programmes. 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 cost-effectively cut building-related emissions.

Appliance standards and labels, building codes, promotion of ESCOs, Clean Development Mechanisms and Joint Implementation (CDM 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 effectively (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 that have much higher ranking in political agendas and thus may enjoy much more resources and a stronger political momentum than climate change mitigation.

9.10.1.1 Policy packages

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 Energy Efficiency Directive (EED) (European Union, 2012) has, since 2008, required Member States to describe co-ordinated packages of policies in their National Energy Efficiency Action Plans (NEEAP). 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, programmes 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 et al., 2010b).

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, lifecycle assessment 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 and 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 change mitigation show that the lifespan of a technical solution is as important as the choice of material, which signals to the importance of related policies such as eco-design directives and mandatory warranties (Mequignon et al., 2013a; b).

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) a large, skilled workforce is needed to carry out high-quality work at relatively low cost.

Implementation and enforcement of policies are key components of effective policy. These two components used together are 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 that 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

Recent reports have comprehensively reviewed building-related policies (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 are 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: (1) 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; (2) property taxation (e.g., related to a building's CO_2 emissions); and (3) progressive appliance standards and building codes, for example, with absolute consumption limits (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 et al., 2010a; 2013a).

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 NZEB mandates, which 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 lifecycle 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 (Moniteur Belge, 2011; BE, 2012; CSTC, 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 et al., 2011b). 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 stabilizing, or even slowing 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., 2010a) 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 United States. Market liberalization initially led to a reduction in such activity (Ürge-Vorsatz et al., 2012b), 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 incentivize 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 Financing opportunities

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).

Another example is the '*Green Deal*', which is a new initiative by the UK government designed to facilitate the retrofitting of energy saving measures to all buildings. Such schemes allows for charges on electricity bills in order to recoup costs of building 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 subsidize 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 United States with Property Assessed Clean Energy (PACE) legislation in place, municipality governments offer a specific bond to investors and then use this to finance lending to consumers and businesses 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 United States. 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 and Limaye, 2011) by governmental agencies. Financing environments for ESCOs need to be improved to ensure they operate optimally and sources of financing, such as debt and equity, need to be located. Possible financing sources are commercial banks, venture capital firms, equity funds, leasing companies, and equipment manufacturers (Da-li, 2009). In social housing in Europe, funding can be provided through Energy Performance Certificates (EPC), 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).

9.10.3.2 Opportunities in financing for green buildings

The existing global green building market is valued at approximately 550 billion USD_{2010} 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). For example, 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 programme 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, until recently it 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 projects 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 USD_{2010} 3.3 billion, of which USD_{2010} 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 chlorofluorocarbon-free (CFC) 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 219 million USD_{2010} 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:

- The lack of adequate bottom-up data leads to a dominance of top down and supply-focused decisions about energy systems.

- Misinformation and simplified techniques pose risks to providing a full understanding of integrated and regionally adequate building systems, and this leads to fragmented actions and weaker results.
- Weak or poor information about opportunities and costs affects optimal decisions and appropriate allocation of financial resources.
- Energy indicators relate to efficiency, but rarely to sufficiency.
- Improved and more comprehensive databases on real, measured building energy use, and capturing behaviour and lifestyles are necessary to develop exemplary practices from niches to standard.
- Continuous monitoring and constant modification of performance and dynamics of codes would allow implementation to catch up with the potential for efficiency improvements and co-benefits; this would also provide 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 should be 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 buildings. 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 9.2 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 et al., 2012c). 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 et al., 2012c). 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 24 billion USD_{2010} in cumulative additional investment needs for realizing these advanced scenarios, but estimates an over 65 billion USD_{2010} in cumulative energy cost savings until 2050.

FAQ 9.3 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 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.

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