CHAPTER 4

Energizing Development without Compromising the Climate

With the global economy set to quadruple by midcentury, energy-related carbon dioxide (CO_2) emissions would, on current trends, more than double, putting the world onto a potentially catastrophic trajectory that could lead to temperatures more than 5°C warmer than in preindustrial times. That trajectory is not inevitable. With concerted global action to adopt the right policies and low-carbon technologies, the means exist to shift to a more sustainable trajectory that limits warming to close to 2°C. In the process, there is an opportunity to produce enormous benefits for economic and social development through energy savings, better public health, enhanced energy security, and job creation.

Such a sustainable energy path requires immediate action by all countries to become much more energy efficient and achieve significantly lower carbon intensity. The path requires a dramatic shift in the energy mix from fossil fuels to renewable energy and possibly nuclear power, along with widespread use of carbon capture and storage (CCS). This, in turn, requires major cost reductions in and widespread diffusion of renewable energy technologies, safeguards for containment of nuclear waste and weapons proliferation, and breakthroughs in technologies from batteries to carbon capture and storage. And it also requires fundamental shifts in economic development and lifestyles. If even one of these requirements is not met, keeping temperature increases close to 2°C above preindustrial levels may be impossible.

In order to limit warming to 2°C, global emissions would have to peak no later than 2020 and then decline by 50–80 percent from today's levels by 2050, with further reductions continuing to 2100 and beyond. Delaying actions by 10 years would make it impossible to reach this goal. The inertia in energy capital stocks means that investments over the next decade will largely determine emissions through 2050 and beyond. Delays would lock the world into high-carbon infrastructure, later requiring costly retrofitting and premature scrapping of existing capital stocks.

Governments should not use the current financial crisis as an excuse to delay climate change actions. The future climate crisis is likely to be far more damaging to the world economy. The economic downturn may delay business-as-usual growth in emissions by a few years, but it is unlikely to fundamentally change that path over the long

Key messages

Solving the climate change problem requires immediate action in all countries and a fundamental transformation of energy systems—significant improvement in energy efficiency, a dramatic shift toward renewable energy and possibly nuclear power, and widespread use of advanced technologies to capture and store carbon emissions. Developed countries must lead the way and drastically cut their own emissions by as much as 80 percent by 2050, bring new technologies to market, and help finance developing countries' transition onto clean energy paths. But it is also in developing countries' interests to act now to avoid locking into high-carbon infrastructure. Many changes—such as removing distortionary price signals and increasing energy efficiency—are good both for development and the environment.

term. Instead, the downturn offers opportunities for governments to direct stimulus investment toward efficient and clean energy to meet the twin goals of revitalizing economic growth and mitigating climate change (box 4.1).

Governments can adopt climate-smart domestic policies now to deploy existing low-carbon technologies while a global climate deal is negotiated. Energy efficiency is the largest and lowest-cost source of emission reductions and is fully justified by development benefits and future energy savings. The potential is huge on both the energy supply side (as in the burning of coal, oil, and gas and the production, transmission, and distribution of electricity) and on the demand side (use of energy in buildings, transport, and manufacturing). But the fact that so much efficiency potential remains untapped suggests that it is not easily realized. Achieving significant energy savings requires price increases and the removal of fossil-fuel subsidies as well as a concerted strategy to tackle market failures and nonmarket barriers with effective regulations, financial incentives, institutional reforms, and financing mechanisms.

The second-largest source of potential emission reductions comes from use of low- to zero-emission fuels for power generation—particularly renewable energy. Many of these technologies are commercially available today, have benefits for development, and can be deployed much more widely under the right policy frameworks. Scaling them up requires putting a price on carbon and providing financial incentives to deploy low-carbon technologies. Large-scale deployment will help reduce their costs and make them more competitive.

But these win-wins, good for both development and climate change, are simply not enough to stay on a 2°C trajectory. Not-yet-proven advanced technologies, such as carbon capture and storage, are needed urgently and on a large scale. Accelerating their widespread availability and use will require greatly enhanced research, development, and demonstration as well as technology sharing and transfer.

An economywide, market-based mechanism, such as a carbon cap-and-trade program or a carbon tax (see chapter 6), is essential to unleash robust private sector investment and innovation to achieve deep emission cuts at least cost. Within governments, coordinated and integrated approaches are needed to achieve low-carbon economies while minimizing the risks of social and economic disruptions.

Developed countries must take the lead in committing to deep emission cuts, pricing carbon, and developing advanced technologies. That is the surest way to trigger development of the needed technologies and ensure their availability at a competitive price. But unless developing countries also start transforming their energy systems as they grow, limiting warming to close to 2°C above preindustrial levels will not be achievable. That transformation requires transfers of substantial financial resources and low-carbon technologies from developed to developing countries.

Energy mitigation paths, and the mix of policies and technologies necessary to reach them, differ among high-, middle-, and low-income countries, depending on their economic structures, resource endowments, and institutional and technical capabilities. A dozen high- and middle-

BOX 4.1 *The financial crisis offers an opportunity for efficient and clean energy*

The financial crisis brings both challenges and opportunities to clean energy. Sharply falling fossil-fuel prices discourage energy conservation and make renewable energy less competitive. The weak macroeconomic environment and tight credit have led to lower demand and declining investment, and renewable energy is hard hit because of its capital-intensive nature (renewable energy is characterized by high up-front capital costs but low operating and fuel costs). By the final quarter of 2008 clean energy investments dropped by more than half from their peak at the end of 2007.[a]

Yet the financial crisis should not be an excuse to delay climate-change action, for it offers opportunities to shift to a low-carbon economy (see chapter 1). First, stimulus investments in energy efficiency, renewable energy, and mass transit can create jobs and build an economy's productive capacity.[b] Second, falling energy prices provide a unique opportunity to implement programs to eliminate fossil-fuel subsidies in emerging economies and adopt fuel taxes in advanced economies in ways that are politically and socially acceptable.

Sources: WDR team based on
a. World Economic Forum 2009.
b. Bowen and others 2009.

income countries account for two-thirds of global energy-related emissions, and their emission reductions are essential to avoid dangerous climate change. This chapter analyzes the mitigation paths and challenges facing some of these countries. It also presents a portfolio of policy instruments and clean energy technologies that can be used to follow the 2°C trajectory.

Balancing competing objectives

Energy policies have to balance four competing objectives—sustain economic growth, increase energy access for the world's poor, enhance energy security, and improve the environment—tall orders. Fossil-fuel combustion produces around 70 percent of greenhouse gas emissions[1] and is the primary source of harmful local air pollution. Many win-win options can mitigate climate change and abate local air pollution through reducing fossil-fuel combustion (box 4.2). Other options present tradeoffs that need to be weighed. For example, sulfates emitted when coal is burned damage human health and cause acid rain, but they also have local cooling effects that offset warming.

Developing countries need reliable and affordable energy to grow and to extend service to the 1.6 billion people without electricity and the 2.6 billion without clean cooking fuels. Increasing access to electricity services and clean cooking fuels in many low-income developing countries, particularly in South Asia and Sub-Saharan Africa, would add less than 2 percent to global CO_2 emissions.[2] Replacing traditional biomass fuels used for cooking and heating with modern energy supplies can also reduce emissions of black carbon—an important contributor to global warming[3]—improve the health of women and children otherwise exposed to high levels of indoor air pollution from traditional biomass, and reduce deforestation and land degradation (see chapter 7, box 7.10).[4]

Energy supplies also face adaptation challenges. Rising temperatures are likely to increase demand for cooling and reduce demand for heating.[5] Higher demand for cooling strains electricity systems, as in the European heat wave of 2007. Climate extremes accounted for 13 percent of the variation in energy productivity in developing countries in 2005.[6] Unreliable or changing precipitation patterns affect the reliability of hydropower. And droughts and heat waves that affect the availability and temperature of water hamper thermal and nuclear energy production,[7] because the plants require substantial quantities of water for cooling—as in the case of power shortages in France during the 2007 heat wave.

The challenge then is to provide reliable and affordable energy services for economic growth and prosperity without compromising the climate. Low-income countries now account for only 3 percent of global energy demand and energy-related emissions. While their energy demand will increase with rising income, their emissions are projected to remain a small share of global emissions in 2050. But middle-income countries, many with expanding economies and a large share of heavy industry, face huge energy needs. And developed countries demand enormous amounts of energy to maintain their current lifestyles.

Low-carbon energy choices can substantially improve energy security by reducing price volatility or exposure to disruptions in energy supplies.[8] Energy efficiency can reduce energy demand, and renewable energy diversifies the energy mix and reduces exposure to fuel price shocks.[9]

But coal, the most carbon-intensive fossil fuel, is abundant near many high-growth areas and provides low-cost and secure energy supplies. Recent oil price swings and uncertainty about gas supplies are leading to increased interest in new coal-fired power plants in many countries (developed and developing). Reducing reliance on oil and gas imports by turning to coal-to-liquid and coal-to-gas production would substantially increase CO_2 emissions. Global coal consumption has grown faster than consumption of any other fuel since 2000, presenting a formidable dilemma between economic growth, energy security, and climate change.

Faced with such challenges and competing objectives, the market alone will not deliver efficient and clean energy in the time and at the scale required to prevent

BOX 4.2 *Efficient and clean energy can be good for development*

Valuing the co-benefits of energy efficiency and clean energy for development—more energy savings, less local air pollution, greater energy security, more employment in local industry, and greater competitiveness from higher productivity—can justify part of the mitigation cost and increase the appeal of green policies. Energy savings could offset a significant share of mitigation costs.[a] The actions needed for the 450 parts per million (ppm) CO_2e concentrations associated with keeping warming at 2°C could reduce local air pollution (sulfur dioxide and nitrogen oxides) by 20–35 percent compared with business as usual in 2030.[b] In 2006 the renewable energy industry created 2.3 million jobs worldwide (directly or indirectly), and energy efficiency added 8 million jobs in the United States.[c] The energy-efficiency and technology-innovation programs in California over the past 35 years have actually increased gross state product.[d]

Many countries, both developed and developing, are setting targets and policies for clean energy technologies (see table). Many of these initiatives are driven by domestic development benefits, but they can also reduce CO_2 emissions substantially. The Chinese government's target of a 20 percent reduction in energy intensity from 2005 to 2010 would reduce annual CO_2 emissions by 1.5 billion tons by 2010, the most aggressive emission reduction target in the world, five times the 300-million-ton reduction of the European Union's Kyoto commitment and eight times the 175-million-ton reduction of the California emission reduction target.[e]

Sources:
a. IEA 2008b; McKinsey & Company 2009a.
b. IEA 2008c.
c. EESI 2008;
d. Roland-Holst 2008.
e. Lin 2007.

Many countries have national plans or proposals for energy and climate change

Country	Climate change	Renewable energy	Energy efficiency	Transport
European Union	20 percent emission reduction from 1990 to 2020 (30 percent if other countries commit to substantial reductions); 80 percent reduction from 1990 to 2050	20 percent of primary energy mix by 2020	20 percent energy savings from the reference case by 2020	10 percent transport fuel from biofuel by 2020
United States	Emission reduction to 1990 levels by 2020; 80 percent reduction from 1990 to 2050	25 percent of electricity by 2025		Increase fuel economy standard to 35 miles a gallon by 2016
Canada	20 percent reduction from 2006 to 2020			
Australia	15 percent reduction from 2000 to 2020			
China	National Climate Change Plan and White Paper for Policies and Actions for Climate Change, a leading group on energy conservation and emission reduction established, chaired by the prime minister	15 percent of primary energy by 2020	20 percent reduction in energy intensity from 2005 to 2010	35 miles a gallon fuel economy standard already achieved; plan to be the world leader in electric vehicles; and mass construction of subways under way
India	National Action Plan on Climate Change: per capita emissions not to exceed developed countries', an advisory council on climate change created, chaired by the prime minister	23 gigawatts of renewable capacity by 2012	10 gigawatts of energy savings by 2012	Urban transport policy: increase investment in public transport
South Africa	Long-term mitigation scenario: emissions peak in 2020 to 2025, plateau for a decade, and then decline in absolute terms	4 percent of the power mix by 2013	12 percent energy-efficiency improvement by 2015	Plan to be the world leader in electric vehicles; and expand bus rapid transit
Mexico	50 percent emission reduction from 2002 to 2050; national strategy on climate change: intersecretariat commission on climate change set up for coordination	8 percent of the power mix by 2012	Efficiency standards, cogeneration	Increase investment in public transport
Brazil	National plan on climate change: reducing deforestation 70 percent by 2018	10 percent of the power mix by 2030	103 terawatt hours of energy savings by 2030	World leader in ethanol production

Sources: Government of China 2008; Government of India 2008; Government of Mexico 2008; Brazil Interministerial Committee on Climate Change 2008; Pew Center 2008a; Pew Center 2008b; Project Catalyst 2009.

Note: Some of the above goals represent formal commitments, while others are still under discussion.

dangerous climate change. Pollution needs to be priced. Achieving the needed progress in energy efficiency requires price incentives, regulations, and institutional reforms. And the risks and scale of the investments in unproven technologies call for substantial public support.

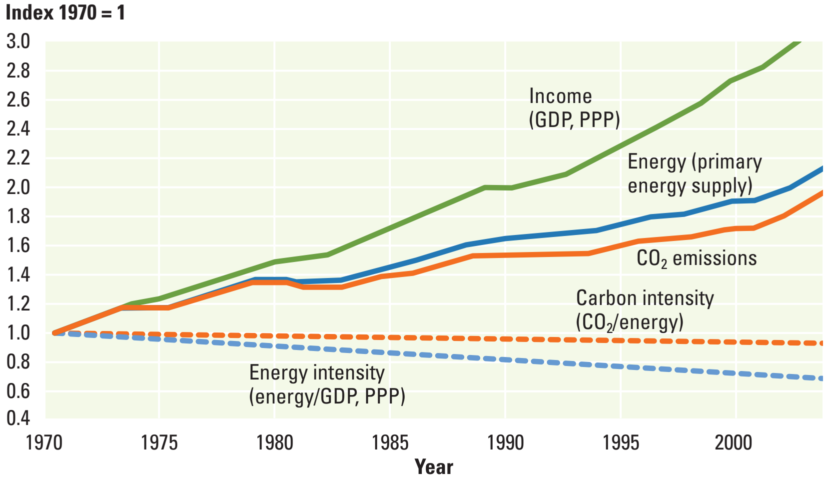
Breaking the high-carbon habit

Carbon emissions from energy are determined by the combination of total energy consumption and its carbon intensity (defined as the units of CO_2 produced by a unit of energy consumed). Energy consumption increases with income and population but with sizable variation depending on economic structure (manufacturing and mining are more energy intensive than agriculture and services), climate (which affects the need for heating or cooling), and policies (countries with higher energy prices and more stringent regulations are more energy efficient). Similarly, the carbon intensity of energy varies depending on domestic energy resources (whether a country is rich in coal or hydro potential) and policies. So the policy levers for a low-carbon growth path include reducing energy intensity (defined as energy consumed per dollar of gross domestic product, or GDP) by increasing energy efficiency and shifting to low-energy-consuming lifestyles—and reducing carbon intensity of energy by shifting to low-carbon fuels such as renewable energy.

A doubling of energy consumption since the 1970s combined with near-constant carbon intensity has resulted in a doubling of emissions (figure 4.1). Energy intensity has improved but far too little to offset the tripling in world income. And carbon intensity has remained relatively constant as achievements in producing cleaner energy have been largely offset by a massive increase in the use of fossil fuels. Fossil fuels dominate global energy supplies, accounting for more than 80 percent of the primary energy mix (figure 4.2).[10]

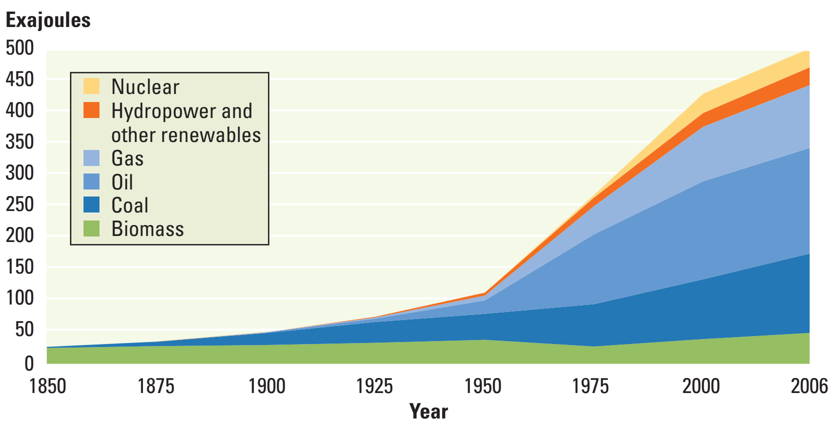
Developed countries are responsible for about two-thirds of the cumulative energy-related CO_2 now in the atmosphere.[11] They also consume five times more energy per capita, on average, than developing countries. But developing countries already account for 52 percent of annual energy-related emissions, and their energy consumption is increasing rapidly—90 percent of the projected increases in global energy consumption, coal use, and energy-related CO_2 emissions over the next 20 years will likely be in developing countries.[12] Projections suggest that because such a large share of global population is in developing countries, they will use 70 percent more total

Figure 4.1 The story behind doubling emissions: improvements in energy and carbon intensity have not been enough to offset rising energy demand boosted by rising incomes



Source: IPCC 2007.
Note: GDP is valued using purchasing power parity (PPP) dollars.

Figure 4.2 Primary energy mix 1850–2006. From 1850 to 1950 energy consumption grew 1.5 percent a year, driven mainly by coal. From 1950 to 2006 it grew 2.7 percent a year, driven mainly by oil and natural gas.

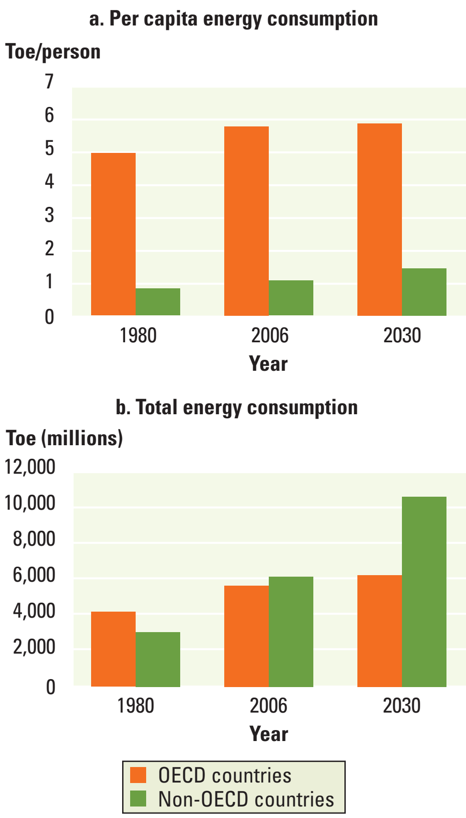


Source: WDR team, based on data from Grübler 2008 (data for 1850–2000) and IEA 2008c (data in 2006).
Note: To ensure consistency of the two data sets, the substitution equivalent method is used to convert hydropower to primary energy equivalent—assuming the amount of energy to generate an equal amount of electricity in conventional thermal power plants with an average generating efficiency of 38.6 percent.

energy annually than developed countries by 2030, even though their energy use per capita will remain low (figure 4.3).

Globally, power is the largest single source of greenhouse gas emissions (26 percent), followed by industry (19 percent), transport (13 percent), and buildings (8 percent),[13] with land-use change, agriculture, and waste accounting for the balance (figure 4.4). The picture varies, however, across income groups. High-income country emissions are dominated by power and transport, while land-use change and agriculture are the leading emission sources in low-income countries. In middle-income countries, power, industry, and land-use change are the largest contributors—but with land-use change emissions concentrated in a handful of countries (Brazil and Indonesia account for half the global land-use change emissions). Power will most likely continue to be the largest source, but emissions are expected to rise faster in transport and industry.

Figure 4.3 Despite low energy consumption and emissions per capita, developing countries will dominate much of the future growth in total energy consumption and CO_2 emissions



Source: WDR team, based on data from IEA 2008c.
Note: Toe = tons of oil equivalent

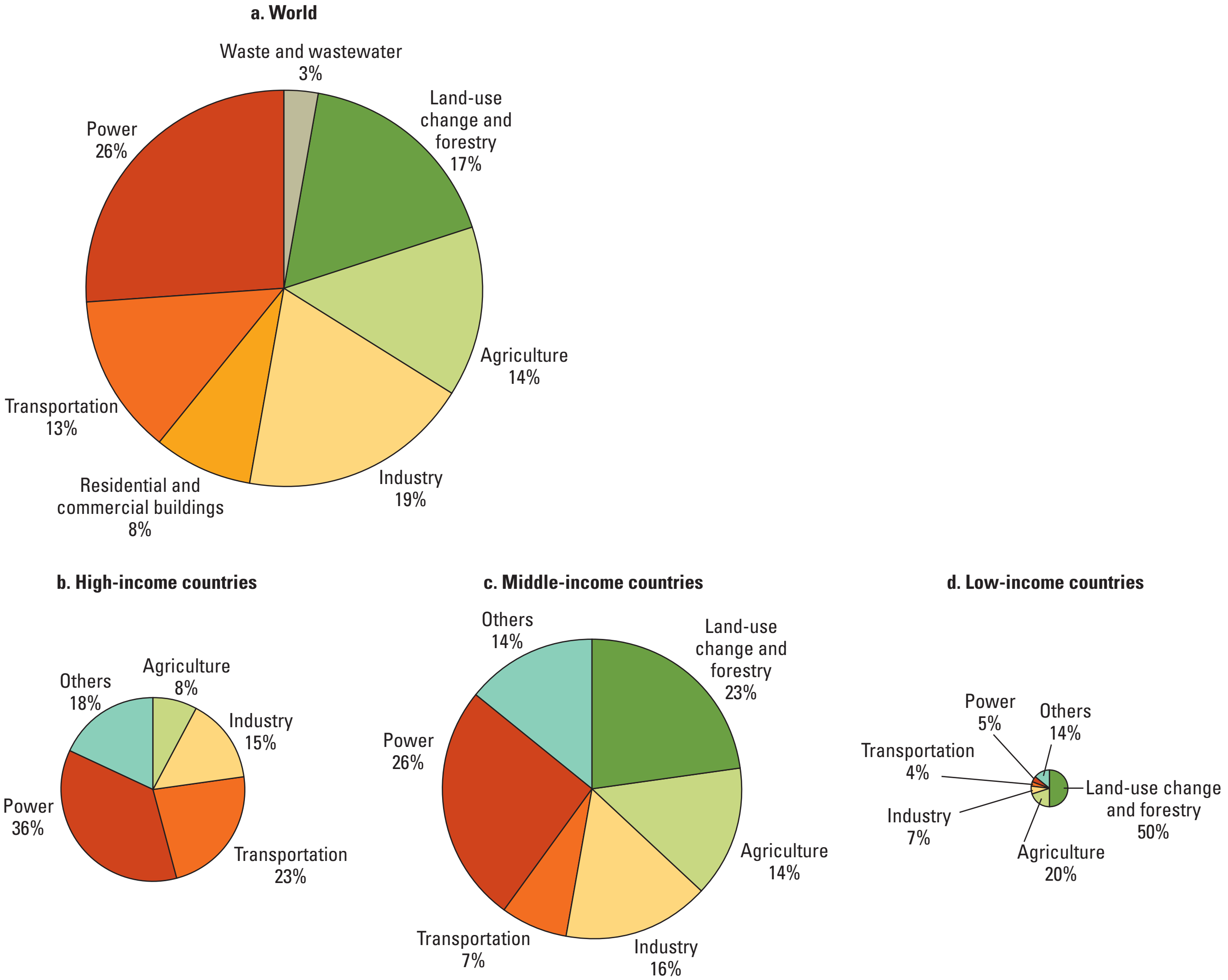
As major centers of production and concentrations of people, the world's cities now consume more than two-thirds of global energy and produce more than 70 percent of CO_2 emissions. The next 20 years will see unprecedented urban growth—from 3 billion people to 5 billion, mostly in the developing world.[14] From now to 2050 building stocks will likely double,[15] with most new construction in developing countries. If cities grow through sprawl rather than densification, demand for travel will increase in ways not easily served by public transport.

Car ownership rates increase rapidly with rising incomes. On current trends 2.3 billion cars will be added between 2005 and 2050, more than 80 percent of them in developing countries.[16] But if the right policies are in place, increased rates of ownership do not have to translate into similar increases in car use (figure 4.5).[17] Because car use drives energy demand and emissions from transport, pricing policies (such as road pricing and high parking fees), public transport infrastructure, and urban form can make a big difference.

Developing countries can learn from Europe and developed Asia to decouple car ownership from car use. European and Japanese drivers travel 30–60 percent fewer vehicle kilometers than drivers in the United States with comparable incomes and car ownership. Hong Kong, China, has one-third the car ownership of New York, the American city with the lowest ratio of cars per capita.[18] How? Through a combination of high urban density, high fuel taxes and road-pricing policies, and well-established public transport infrastructure. Similarly, Europe has four times the public transport routes per 1,000 persons as the United States.[19] But in many developing countries, public transport has not kept up with urban growth, so the move to individual car ownership is causing chronic and increasing problems of congestion.

Transport infrastructure also affects settlement patterns, with a high volume of roads facilitating low-density settlements

Figure 4.4 Greenhouse gas emissions by sector: world and high-, middle-, and low-income countries



Source: WDR team, based on data from Barker and others 2007 (figure 4a) and WRI 2008 (figures 4b, c, and d).

Note: The sectoral share of global emissions in figure 4.4a is for 2004. The sectoral share of emissions in high-, middle-, and low-income countries in figures 4.4b, 4.4c, and 4.4d are based on emissions from the energy and agriculture sectors in 2005 and from land-use changes and forestry in 2000. The size of each pie represents contributions of greenhouse gas emissions, including emissions from land-use changes, from high-, middle-, and low-income countries; the respective shares are 35, 58, and 7 percent. Looking only at CO_2 emissions from energy, the respective shares are 49, 49, and 2 percent. In Figure 4.4a, emissions from electricity consumption in buildings are included with those in the power sector. Figure 4.4b does not include emissions from land-use change and forestry, because they were negligible in high-income countries.

and an urban form that mass transit systems cannot easily serve. Low-density settlements then make it more difficult to adopt energy-efficient district heating for buildings.[20]

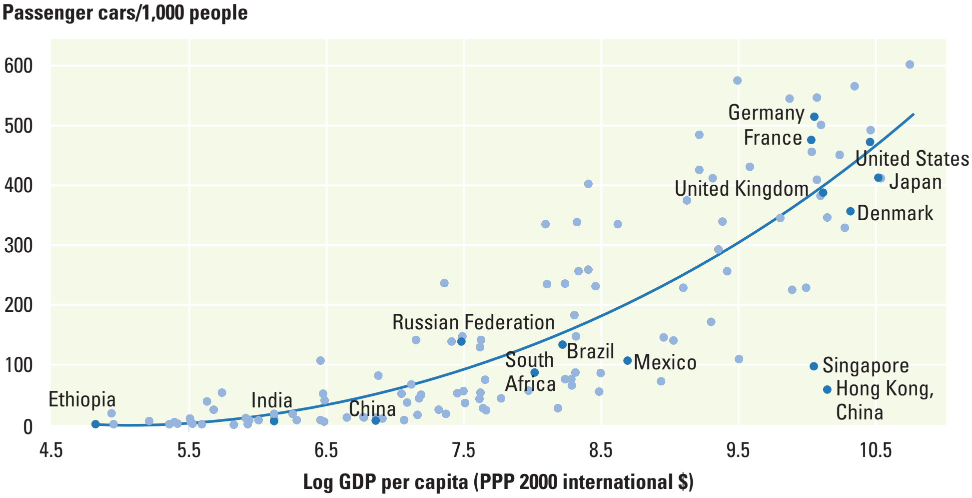
Where the world needs to go: Transformation to a sustainable energy future

Achieving sustainable and equitable growth and prosperity requires that high-income countries significantly reduce their emissions—and their emissions per capita (blue arrows in figure 4.6). It also depends on developing countries avoiding the carbon-intensive path followed by developed countries such as Australia or the United States, taking instead a low-carbon growth path (orange arrow). It thus requires fundamental changes in lifestyles for developed countries and a leapfrogging to new development models for developing countries.

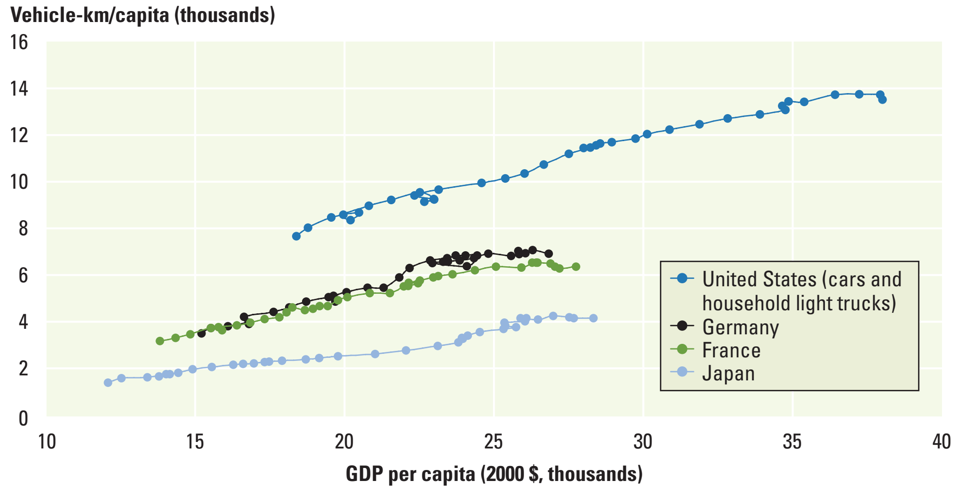
Achieving these goals requires reconciling what is adequate to prevent dangerous climate change with what is technically

Figure 4.5 Car ownership increases with income, but pricing, public transport, urban planning, and urban density can contain car use

a. Car ownership and income, 2000



b. Car use and income, 1970–2005



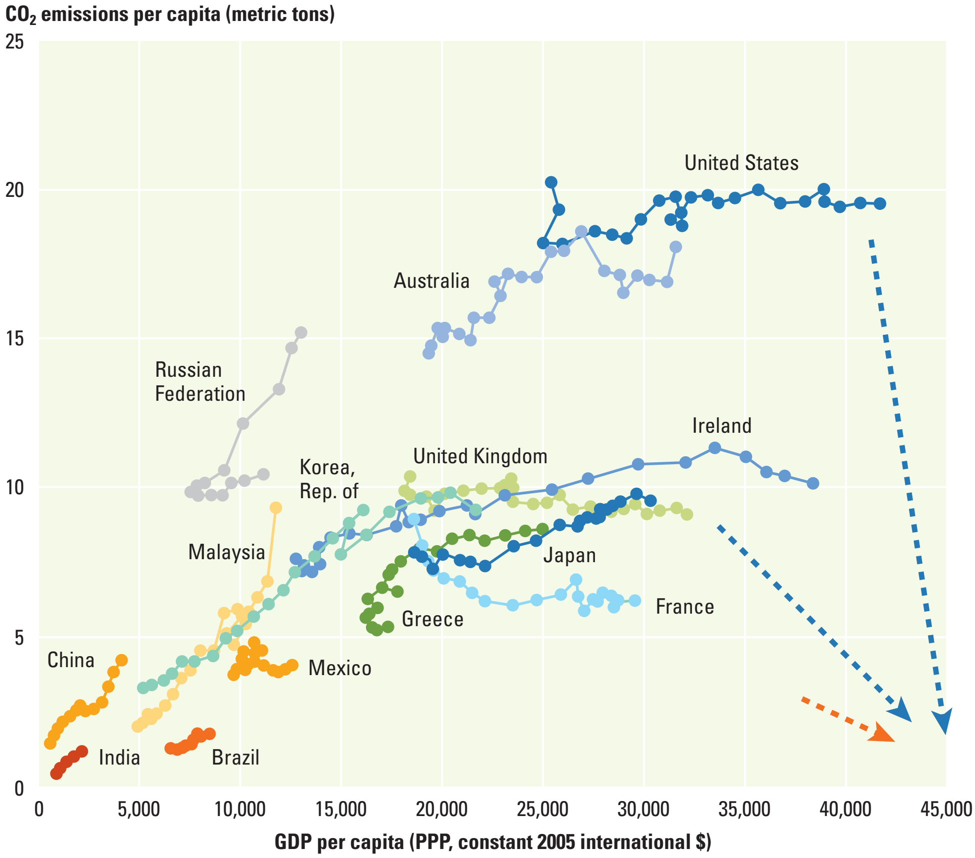
Sources: Schipper 2007; World Bank 2009c.

Note: In figure 4.5b, data are from West Germany through 1992 and for all of unified Germany from 1993 onward. Notice the similarity in rates of car ownership among, the United States, Japan, France, and Germany (panel a) but the large variation in distance traveled (panel b).

achievable at acceptable costs. Limiting warming to not much more than 2°C above preindustrial temperatures means that global emissions must peak no later than 2020, then decline by 50–80 percent from current levels by 2050, with perhaps even negative emissions required toward 2100.[21] This is an ambitious undertaking: only about half of the energy models reviewed find it feasible (figure 4.7), and even then most require all countries to start taking action immediately.

More specifically, staying close to a 2°C warming requires greenhouse gas concentrations in the atmosphere to stabilize at no more than 450 parts per million (ppm) CO_2 equivalent (CO_2e).[22] Current greenhouse gas concentrations are already at 387 ppm CO_2e and are rising at about 2 ppm a year.[23] Thus, there is little room for emissions to grow if warming is to stabilize around 2°C. Most models assume that achieving 450 ppm CO_2e will require overshooting that concentration for a few decades and then coming back to 450 ppm CO_2e toward the end of the century (table 4.1). Faster reductions of short-lived greenhouse gas emissions, such as methane and

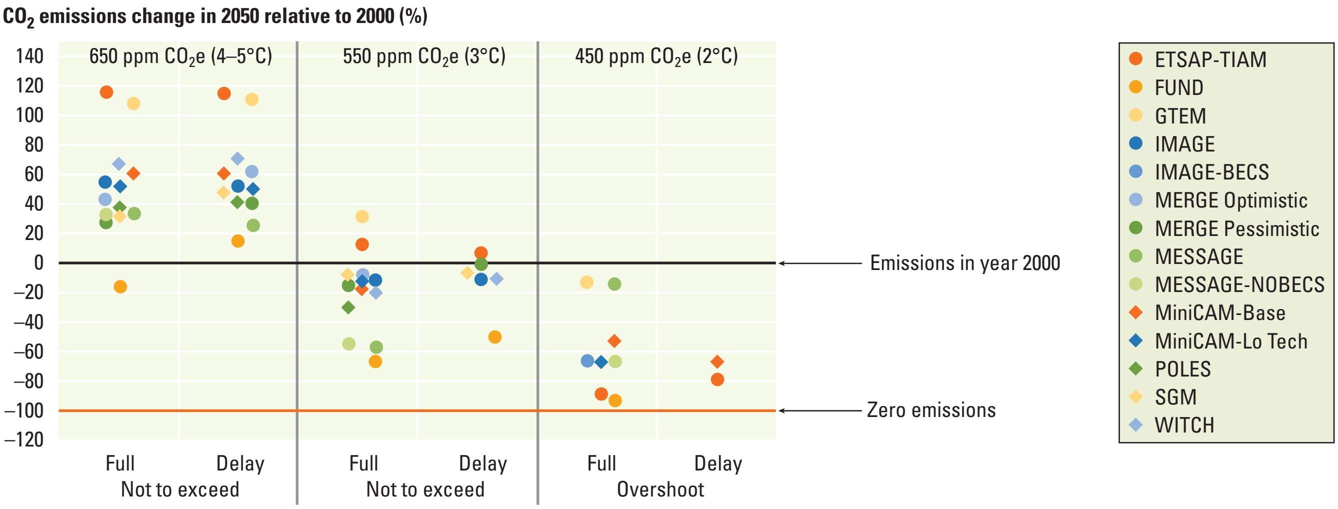
Figure 4.6 Where the world needs to go: Energy-related CO_2 emissions per capita



Source: Adapted from NRC 2008, based on data from World Bank 2008e.

Note: Emissions and GDP per capita are from 1980 to 2005.

Figure 4.7 Only half the energy models find it possible to achieve the emission reductions necessary to stay close to 450 ppm CO_2e (2°C)



Source: Clarke and others, forthcoming.

Note: Each dot represents the emissions reduction that a particular model associates with a concentration target—450, 550, 650 parts per million (ppm) of CO_2 equivalent (CO_2e)—in 2050. The number of dots in each column signals how many of the 14 models and model variants were able to find a pathway that would lead to a given concentration outcome. "Overshoot" describes a mitigation path that allows concentrations to exceed their goal before dropping back to their goal by 2100, while "not to exceed" implies the concentration is not to be exceeded at any time. "Full" refers to full participation by all countries, so that emission reductions are achieved wherever and whenever they are most cost-effective. "Delay" means high-income countries start abating in 2012, Brazil, China, India, and the Russian Federation start abating in 2030, and the rest of the world in 2050.

Table 4.1 What it would take to achieve the 450 ppm CO_2e concentration needed to keep warming close to 2°C—an illustrative scenario

	Not-to-exceed	Overshoot
Immediate participation	1) Immediate participation by all regions 2) 70% dramatic emissions reductions by 2020 3) Substantial transformation of the energy system by 2020, including the construction of 500 new nuclear reactors, and the capture of 20 billion tons of CO_2 4) Carbon price of $100/t$CO_2$ globally in 2020 5) Tax on land-use emissions beginning in 2020	1) Immediate participation by all regions 2) Construction of 126 new nuclear reactors and the capture of nearly a billion tons of CO_2 in 2020 3) Negative global emissions by the end of the century, and thus requires broad deployment of biomass-based CCS 4) Carbon prices escalate to $775/t$CO_2$ in 2095 5) Possible without a tax on land-use emissions, but would result in a tripling of carbon taxes and a substantial increase in the cost of meeting the target.
Delayed participation		1) Dramatic emissions reductions for non-Annex I (developing countries) at the time of their participation 2) Negative emissions in Annex I (high-income) countries by 2050 and negative global emissions by the end of the century, and thus requires broad deployment of biomass-based CCS 3) Carbon prices begin at $50/t$CO_2$, and rise to $2,000/t$CO_2$ 4) Results in significant carbon leakage, because crop production is outsourced to nonparticipating regions resulting in a substantial increase in land-use change emissions in those regions

Source: Clarke and others, forthcoming.

Note: Maintaining emissions at 450 ppm CO_2e or less at all times is almost impossible to attain. If concentrations are allowed to exceed 450 ppm CO_2e before 2100, keeping warming close to 2°C still poses tremendous challenges, as the right-hand column outlines. Annex I countries are the OECD and transition economies committed to reducing emissions under the Kyoto Protocol. The non-Annex I countries did not take on any commitment to reduce emissions.

black carbon, could reduce the overshoot but not avoid it.[24] In addition, 450 ppm CO_2e trajectories rely on biomass-based carbon capture and storage[25] for negative emissions.[26] But given the competition for land and water for food production and carbon storage (see chapter 3), sustainable biomass supplies will be an issue.[27] Limiting warming to 2°C will thus require fundamental changes in the global energy mix (box 4.3 and box 4.4; see endnote 28 for model details).[28]

The mitigation costs of achieving 450 ppm CO_2e are estimated at 0.3–0.9 percent of global GDP in 2030, assuming that all mitigation actions occur whenever and wherever they are cheapest (figure 4.8).[29] This estimate compares to total expenditures in the energy sector of 7.5 percent of GDP today. Moreover, the costs of inaction—from the damages caused by greater warming—may well exceed this mitigation cost (see chapter 1 for a discussion of the cost-benefit analysis of climate policy).

Achieving 450 ppm CO_2e requires the adoption of technologies with marginal costs of $35 to $100 a ton of CO_2 in 2030, for a global annual mitigation investment of $425 billion to $1 trillion in 2030 (table 4.2).[30] Future energy savings would eventually offset a substantial share of the up-front investment.[31] But much of this investment is needed within the next 10 years in financially constrained developing countries. And removing obstacles to reform and directing capital to low-carbon investments where and when they are needed will be challenging.

A less challenging option would be to aim for a higher concentration—for example, 550 ppm CO_2e. That concentration is associated with a 50-percent chance of warming exceeding 3°C, and a higher risk of damages from climate change impacts, but it allows a little more time for emissions to peak (2030). Emissions would need to fall back to today's levels by 2050 and continue to fall substantially thereafter. Mitigation costs of 550 ppm CO_2e are somewhat lower, at 0.2–0.7 percent of global GDP in 2030 (figure 4.8a), and require adoption of technologies with marginal costs up to $25 to $75 a ton of CO_2 in 2030 (figure 4.8b), for average annual additional investments of some $220 billion a year over the next 20 years.[32] Achieving this more modest goal would still require far-reaching policy reforms.

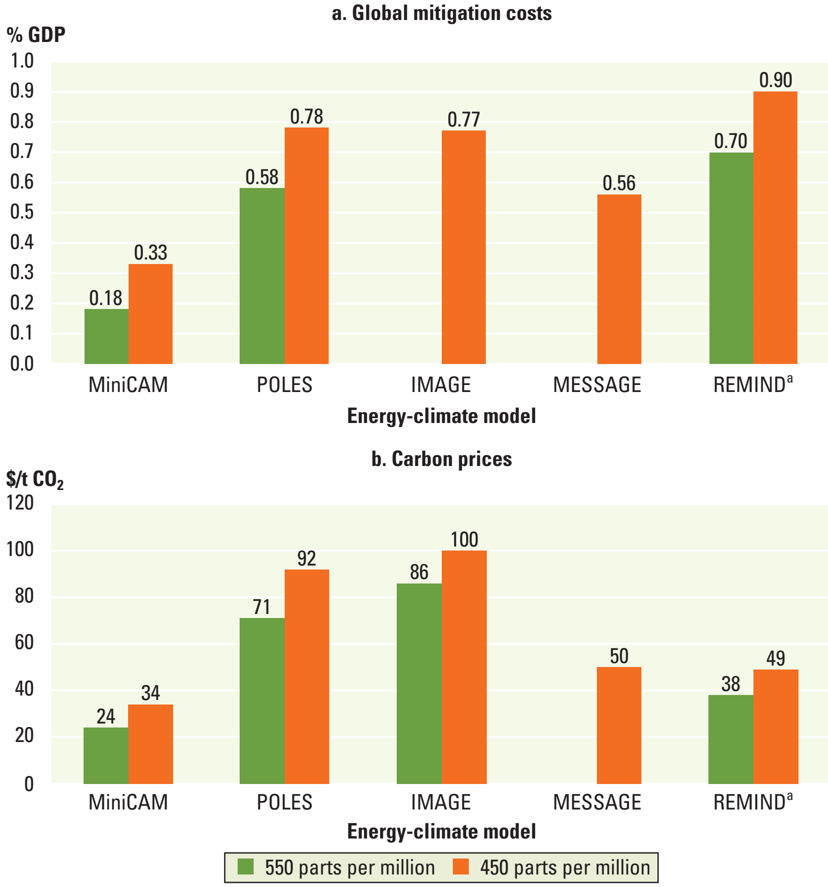
Action—immediate and global

Delaying global actions for more than 10 years makes stabilization at 450 ppm CO_2e impossible.[33] There is little flexibility on the time when emissions peak. To achieve 450 ppm CO_2e, global energy-related CO_2 emissions will need to peak at 28–32 gigatons in 2020 from 26 gigatons in 2005, and then fall to 12–15 gigatons by 2050.[34] This trajectory requires a 2–3 percent cut in emissions each year from 2020 onward. If emissions increase for 10 years beyond 2020, emissions would have to be reduced 4–5 percent a year. In contrast, emissions increased 3 percent a year from 2000 to 2006, so most countries are on their way to a high-carbon path, with total global CO_2 emissions outpacing the worst-case scenario projected by the Intergovernmental Panel on Climate Change (IPCC).[35]

New additions of power plants, buildings, roads, and railroads over the next decade will lock in technology and largely determine emissions through 2050 and beyond. Why? Because the energy capital stock has a long life—it can take decades to turn over power plants, a century to turn over urban infrastructure.[36] Delaying action would substantially increase future mitigation costs, effectively locking the world into carbon-intensive infrastructure for decades to come. Even existing low-cost clean energy technologies will take decades to fully penetrate the energy sector. And given the long lead times for new technology development, deploying advanced technologies on a large scale beginning in 2030 requires aggressive action today.

Delaying action would, in addition, lead to costly retrofitting and early retirement of energy infrastructure. Building to current standards and then retrofitting existing capacity, whether power plants or buildings, would be far more costly than building new, efficient, and low-carbon infrastructure in the first place. The same is true for the forced early retirement of inefficient energy capital. Energy savings often justify the higher up-front investments in new capital, but they are less likely to cover premature replacement of capital stock. Even a high CO_2 price may be insufficient to change this picture.[37]

Figure 4.8 Estimates of global mitigation costs and carbon prices for 450 and 550 ppm CO_2e (2°C and 3°C) in 2030 from five models



Sources: WDR team, based on data from Knopf and others, forthcoming; Rao and others 2008; Calvin and others, forthcoming.

Note: This graphic compares mitigation costs and carbon prices from five global energy-climate models—MiniCAM, IMAGE, MESSAGE, POLES, and REMIND (see note 28 for model assumptions and methodology). MiniCAM, POLES, IMAGE, and MESSAGE report abatement costs for the transformation of energy systems relative to the baseline as a percent of GDP in 2030, where GDP is exogenous.

a. The mitigation costs from REMIND are given as macroeconomic costs expressed in GDP losses in 2030 relative to baseline, where GDP is endogenous.

Table 4.2 Investment needs to limit warming to 2°C (450 ppm CO_2e) in 2030
(constant 2005$ billion)

Region	IEA	McKinsey	MESSAGE	REMIND
Global	846	1013	571	424
Developing countries	565	563	264	384
North America		175	112	
European Union		129	92	
China		263	49	
India		75	43	

Sources: IEA 2008b; Knopf and others, forthcoming and additional data provided by B. Knopf; Riahi, Grübler, and Nakićenović 2007; IIASA 2009 and additional data provided by V. Krey; McKinsey & Company 2009a with further data breakdown provided by McKinsey (J. Dinkel).

BOX 4.3 A 450 ppm CO_2e (2°C warmer) world requires a fundamental change in the global energy system

For this Report the team examined five global energy-climate models that differ in methodology, assumptions about baseline, technology status, learning rates, costs, and inclusion of greenhouse gases (in addition to CO_2). Attainability of a 450 ppm CO_2e trajectory is dependent on the characteristics of the baseline. Some integrated assessment models can not reach a 450 ppm CO_2e trajectory from a fossil-fuel-intensive and high-energy-growth baseline.

A number of models can achieve 450 ppm CO_2e at moderate costs, but each follows different emissions pathways and energy mitigation strategies.[a] Different emission pathways present a tradeoff between emission reductions in the short to medium term (2005–2050) and the long term (2050–2100). A modest emission reduction before 2050 requires dramatically deeper emission cuts over the long term through widespread use of biomass-based carbon capture and storage.[b] These differences in model methodologies and assumptions also result in varying investment needs in the short term (2030), as shown in table 4.2. The models also vary significantly on the energy mix from now to 2050 (see the figure on the facing page), although the stark conclusion does not vary. The policy implication is that a mix of technology options that varies by country and over time is needed—the least-cost strategies all rely on a broad portfolio of energy technologies.

Global energy mix for 450 ppm CO_2e

The 450 ppm CO_2e trajectory requires a global energy revolution—large reductions in total energy demand and major changes in the energy mix. To achieve this, global climate-energy models call for aggressive energy-efficiency measures that dramatically reduce global energy demand from around 900 exajoules by 2050 under a business-as-usual scenario to 650–750 exajoules—a 17–28 percent cut.

Most models project that fossil fuels would need to drop from 80 percent of energy supply today to 50–60 percent by 2050. The future use of fossil fuels (particularly coal and gas) in a carbon-constrained world depends on widespread use of carbon capture and storage (CCS), which would have to be installed in 80–90 percent of coal plants by 2050, assuming that capture-and-storage technology becomes technically and economically feasible for large-scale applications in the next decade or two (table below).[c]

This significant reduction in fossil-fuel use would need to be offset by renewables and nuclear energy. The largest increase would be in renewable energy, which would jump from 13 percent today (mainly traditional biomass fuel and hydropower) to around 30–40 percent by 2050, dominated by modern biomass with and without carbon capture and storage, with the remainder from solar, wind, hydropower, and geothermal (see the figure). Nuclear would also need a boost—from 5 percent today to around 8–15 percent by 2050.[d]

The magnitude of the required effort is substantial: it amounts to an additional 17,000 wind turbines (producing 4 megawatts each), 215 million square meters of solar photovoltaic panels, 80 concentrated solar power plants (producing 250 megawatts each), and 32 nuclear plants (producing 1,000 megawatts each) per year over the next 40 years compared to the baseline.[e] The power sector would need to be virtually decarbonized, followed by the industrial and building sectors (table above).

Cutting energy-related emissions in half by 2050 requires deep decarbonization of the power sector

	Estimated % of carbon that must be removed by sector, 2005–2050	
Sector	**IEA**	**MiniCAM**
Power	–71	–87
Building	–41	–50
Transport	–30	+47
Industry	–21	–71
Total	–50	–50

Sources: WDR team based on data from IEA 2008b; Calvin and others, forthcoming.

The energy mix to achieve 450 ppm CO_2e can vary, but we must make use of all options

	Current energy mix	Energy mix in 2050				
	Global	**Global**	**United States**	**European Union**	**China**	**India**
Energy type	% of total					
Coal without CCS	26	1–2	0–1	0–2	3–5	2–3
Coal with CCS	0	1–13	1–12	2–9	0–25	3–26
Oil	34	16–21	20–26	11–23	18–20	18–19
Gas without CCS	21	19–21	20–21	20–22	9–13	5–9
Gas with CCS	0	8–16	6–21	7–31	1–29	3–8
Nuclear	6	8	8–10	10–11	8–12	9–11
Biomass without CCS	10	12–21	10–18	10–11	9–14	16–30
Biomass with CCS	0	2–8	1–7	3–9	1–12	2–12
Non-biomass renewables	3	8-14	7–12	7–12	10–13	5–19
Total (exajoules a year)	493	665–775	87–121	70–80	130–139	66–68

Sources: WDR team, based on data from Riahi, Grübler, and Nakićenović 2007; IIASA 2009; Calvin and others, forthcoming; IEA 2008b.

Sources:

a. Knopf and others, forthcoming; Rao and others 2008.

b. Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

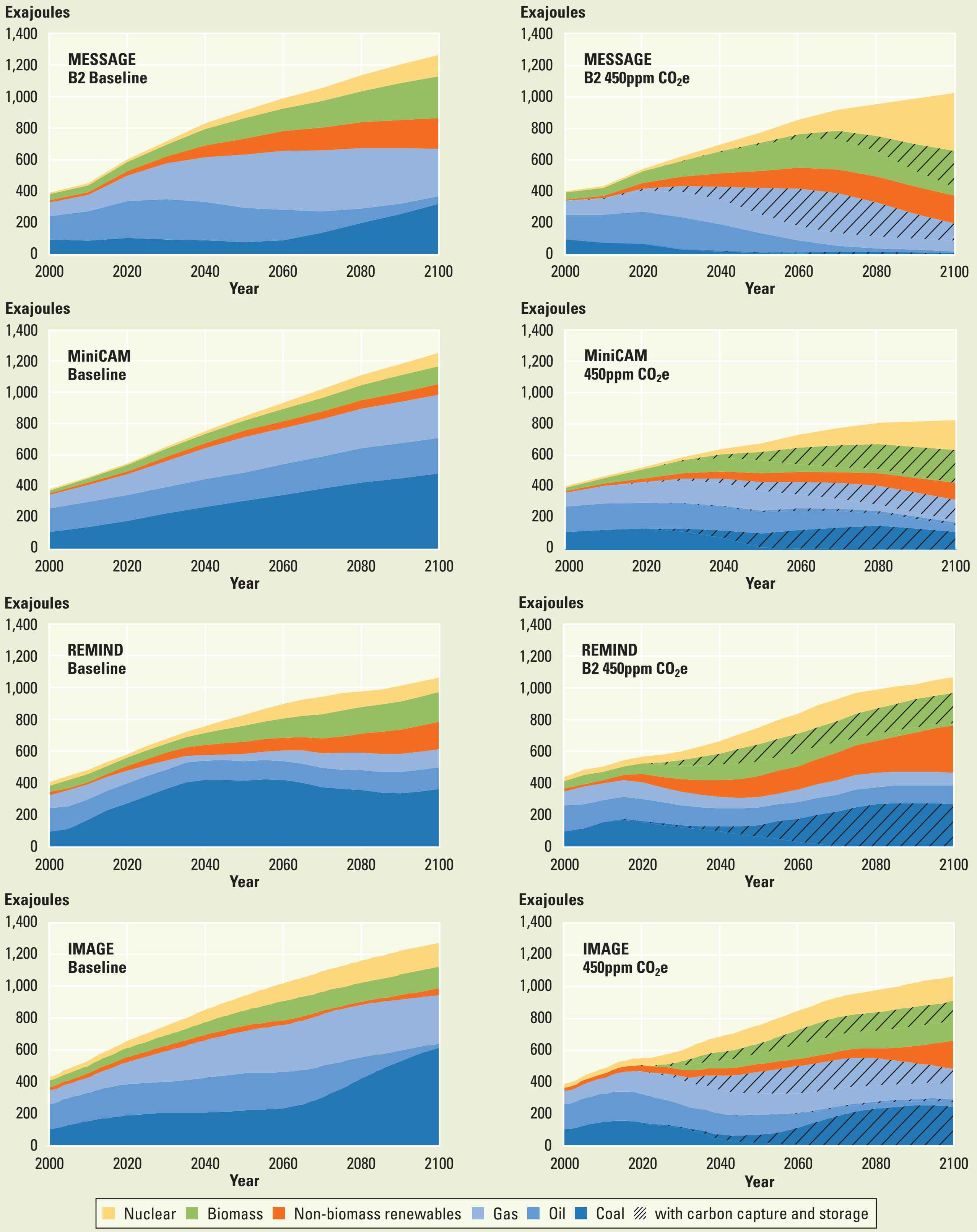
c. IEA 2008b; Calvin and others, forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; van Vuuren and others, forthcoming; Weyant and others 2009.

d. IEA 2008b; Calvin and others, forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; van Vuuren and others, forthcoming.

e. IEA 2008b.

(*continued*)

450 ppm CO_2e requires a fundamental change in the global primary energy mix



BOX 4.4 Regional energy mix for 450 ppm CO_2e (to limit warming to 2°C)

It is important for national policy makers to understand the implications of a 450 ppm CO_2e trajectory for their energy systems. Most integrated assessment models follow a "least-cost" approach, where emission reductions occur wherever and whenever they are cheapest in all sectors and in all countries.[a] But the country in which mitigation measures are taken is not necessarily the one that bears the costs (see chapter 6). It is not the purpose of this chapter to advocate any particular approach to burden sharing or to allocate emission reductions among countries; that is a matter for negotiation.

The United States, the European Union, and China now account for nearly 60 percent of the world's total emissions. India currently contributes only 4 percent of global emissions despite representing 18 percent of the world's population, but its share is projected to increase to 12 percent by 2050 in the absence of mitigation policy. So, these countries' contributions to global emission reductions will be essential to stabilize the climate.

United States and European Union

Energy efficiency could reduce total energy demand in developed countries by 20 percent in 2050 relative to business as usual. This would require an annual decline in energy intensity of 1.5–2 percent over the next four decades, continuing the current trend of the past two decades. To achieve 450 ppm CO_2e the United States and the European Union would need to cut oil consumption significantly by 2050, a substantial challenge because they now consume almost half of global oil production. They would also need to dramatically reduce coal use—a daunting task for the United States, the world's second-largest coal producer and consumer—and widely deploy carbon capture and storage.

The United States and the European Union have the resources to realize these measures and overcome the challenges. Both have abundant renewable energy potential. Some models project that carbon capture and storage would have to be installed for 80–90 percent of coal and gas plants and 40 percent of biomass plants in the United States by 2050 (see lower table of box 4.3). This is potentially feasible given the estimated CO_2 storage capacity. But doubling the share of natural gas in the European primary energy mix from 24 percent today to 50 percent by 2050, assumed by some 450 ppm CO_2e scenarios, may pose energy security risks, particularly given the recent disruption of gas supplies to Europe. The 450 ppm CO_2e scenario requires an additional annual investment of \$110 billion to \$175 billion for the United States (0.8–1 percent of GDP) and \$90 billion to \$130 billion for the European Union (0.6–0.9 percent of GDP) in 2030 (see table 4.2).

China

Significantly reducing emissions below current levels is a formidable goal for China, the world's largest coal producer and consumer. China, relies on coal to meet 70 percent of its commercial energy needs (compared with 24 percent in the United States and 16 percent in Europe). To meet 450 ppm CO_2e, total primary energy demand would have to be 20–30 percent below the projected business-as-usual level by 2050. Energy intensity would have to decline by 3.1 percent a year over the next four decades.

Impressively, Chinese GDP quadrupled from 1980 to 2000 while energy consumption only doubled. After 2000, however, the trend reversed, even though energy intensity continues to fall within industrial subsectors. The main reason: a sharp rise in the share of heavy industry, driven by strong demand from domestic and export production.[b] China produces 35 percent of the world's steel, 50 percent of its cement, and 28 percent of its aluminum. This development stage, when energy-intensive industries dominate the economy, presents great challenges to decoupling emissions from growth.

China has increased the average efficiency of coal-fired power plants by 15 percent over the last decade to an average of 34 percent.A policy that requires closing small-scale coal-fired power plants and substituting large-scale efficient ones over the last two years reduces annual CO_2 emissions by 60 million tons. A majority of new coal-fired plants are equipped with state-of-the-art supercritical and ultrasupercritical technologies.[c]

Despite these advances, China would still have to reduce the share of coal in the primary energy mix dramatically to achieve 450 ppm CO_2e (see the lower table of box 4.3). Renewable energy could meet up to 40 percent of total energy demand in 2050. Several scenarios have extremely ambitious nuclear programs, in which China would build nuclear power plants three times faster than France ever achieved, and nuclear capacity in 2050 would reach seven times France's current nuclear capacity. Given China's limited gas reserves, increasing the percentage of gas in the primary energy mix from the current 2.5 percent to 40 percent by 2050, as assumed by some models, is problematic.

Given the large domestic reserves, coal will likely remain an important energy source in China for decades. Carbon capture and storage is essential for China's economic growth in a carbon-constrained world. Some 450 ppm CO_2e scenarios project that carbon capture and storage would have to be installed for 85–95 percent of coal plants in China by 2050—more than can be accommodated by the current projections of economically available CO_2 storage capacity of 3 gigatons a year within 100 kilometers of the emission sources. But further site assessment, technology breakthrough, and future carbon pricing could change this situation. The 450 ppm CO_2e scenario requires an additional annual investment for China of \$30 billion to \$260 billion (0.5–2.6 percent of GDP) by 2030.

India and other developing countries

India faces tremendous challenges in substantially altering its emissions path given its limited potential for alternative energy resources and for carbon storage sites. Like China, India heavily relies on coal (which accounts for 53 percent of its commercial energy demand). Achieving 450 ppm CO_2e would require a veritable energy revolution in India. Total primary energy demand would have to decline relative to the business-as-usual projections by around 15–20 percent by 2050 and energy intensity by 2.5 percent a year from now to 2050, doubling the efforts of the past decade. A large potential exists, however, for improving energy efficiency and reducing the 29 percent losses in transmission and distribution, to a level closer to the world average of 9 percent. And while the efficiency of coal-fired power plants in India has improved in

(*continued*)

recent years, the average efficiency is still low at 29 percent, and nearly all the coal-fired plants are subcritical.

As in China, coal's share in India's primary energy mix would have to be reduced dramatically to achieve 450 ppm CO_2e. The potential for hydropower (150 gigawatts) and onshore wind power (65 gigawatts) is large in absolute terms but small in relation to future energy needs (12 percent in the power mix by 2050 in the 450 ppm CO_2e scenario). Considerable untapped possibilities exist for importing natural gas and hydropower from neighboring countries, but difficulties remain in establishing transboundary energy trade agreements. For solar to play a large role, costs would have to come down significantly. Some models suggest that India would need to rely on biomass to supply 30 percent of its primary energy by 2050 under the 450 ppm CO_2e scenario. But this may exceed India's sustainable biomass potential because biomass production competes with agriculture and forests for land and water.

India has limited economically available carbon storage sites, with a total storage capacity of less than 5 gigatons of CO_2, enough to store only three years of carbon if 90 percent of coal plants were equipped with carbon capture and storage by 2050, as some 450 ppm CO_2e scenarios project. Additional site assessments and technology breakthroughs could change this. The 450 ppm CO_2e scenario requires an additional annual investment of \$40 billion to \$75 billion for India (1.2–2.2 percent of GDP) in 2030.

Sub-Saharan Africa (excluding South Africa) contributes 1.5 percent of global annual energy-related CO_2 emissions today, an amount projected to grow to only 2–3 percent by 2050. Providing basic modern energy services to the poor should be the top priority and will only slightly increase global greenhouse gas emissions. But a global clean energy revolution is relevant to the low-income countries, which may be able to leapfrog to the next generation of technologies. Clean energy can play a large role in increasing access to energy, and pursuing energy efficiency is a cost-effective short-term solution to power outages.

According to climate-energy models, under the 450 ppm CO_2e scenarios, most developing countries would need to boost their production of renewable energy. Africa, Latin America, and Asia could contribute by switching to modern biomass. And Latin America and Africa have substantial untapped hydropower, although the amount could be affected by a less reliable hydrological cycle resulting from climate change. These countries would also need a major boost in natural gas.

Sources: Calvin and others, forthcoming; Chikkatur 2008; Dahowski and others 2009; de la Torre, Fajnzylber, and Nash 2008; Dooley and others 2006; German Advisory Council on Global Change 2008; Government of India Planning Commission 2006; Holloway and others 2008; IEA 2008b; IEA 2008c; IIASA 2009; Lin and others 2006; McKinsey & Company 2009a; Riahi, Grübler, and Nakićenović 2007; Wang and Watson 2009; Weber and others 2008; World Bank 2008c; Zhang 2008.

a. They are based on an integrated global carbon market and do not consider any explicit burden sharing between countries. In reality, this is unlikely. Burden sharing is discussed in chapter 1, and the implication of delayed participation by non-Annex I countries is discussed in chapter 6. We also reviewed models from developing countries (China and India), but no public information is available for 450 ppm CO_2e scenarios.

b. Lin and others 2006. Production of exports accounted for around one-third of China's emissions in 2005 (Weber and others 2008).

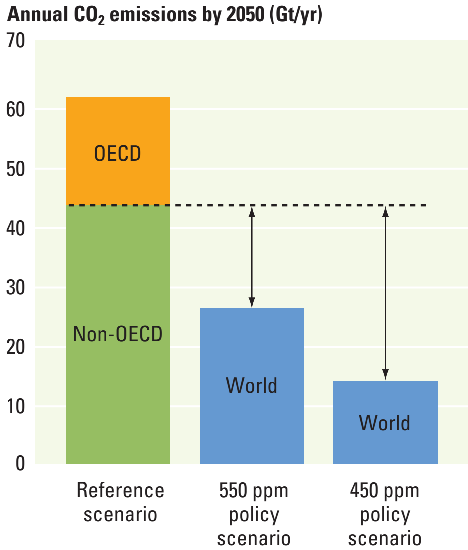
c. Supercritical and ultrasupercritical plants use higher steam temperatures and pressures to achieve higher efficiency of 38–40 percent and 40–42 percent respectively, compared with large subcritical power plants with an average efficiency of 35–38 percent.

To avoid such lock-ins, the scale and rate of urbanization present an unrivaled opportunity, particularly for developing countries, to make major decisions today about building low-carbon cities with compact urban designs, good public transport, efficient buildings, and clean vehicles.

One beneficial feature of the inertia in energy infrastructure is that introducing efficient low-carbon technologies into new infrastructure offers an opportunity to lock in a low-carbon path. Developing countries will install at least half the long-lived energy capital stocks built between now and 2020.[38] For example, half of China's building stock in 2015 will have been built between 2000 and 2015.[39] There are fewer opportunities in developed countries, where residential buildings tend to have slow retirements—60 percent of France's expected residential building stock in 2050 has already been built. This fact constrains the potential for reductions in heating and cooling demand, which requires retrofitting and replacing building shells. But there are abundant opportunities over the next decade in both developed and developing countries to build new power plants with clean energy technologies, thereby avoiding further lock in to carbon-intensive fuels.

For the reasons outlined in the Bali Action Plan, which is shaping the current negotiations under the United Nations Framework Convention on Climate Change, developed countries must take the lead in cutting emissions (see chapter 5). But developed countries alone could not put the world onto a 2°C trajectory, even if they were able to reduce their emissions to zero (figure 4.9). By 2050, 8 billion of the world's 9 billion people will live in today's developing countries, producing 70 percent of projected global emissions.[40] Developed countries can, however, provide financial assistance and

Figure 4.9 Global actions are essential to limit warming to 2°C (450 ppm) or 3°C (550 ppm). Developed countries alone could not put the world onto a 2°C or 3°C trajectory, even if they were to reduce emissions to zero by 2050.



Sources: Adapted from IEA 2008b; Calvin and others, forthcoming.

Note: If energy-related emissions from developed countries (orange) were to reduce to zero, emissions from developing countries (green) under business as usual would still exceed global emission levels required to achieve 550 ppm CO_2e and 450 ppm CO_2e scenarios (blue) by 2050.

Table 4.3 Different country circumstances require tailored approaches

Countries	Low-carbon technologies and policies
Low-income countries	Expand energy access through grid and off-grid options
	Deploy energy efficiency and renewable energy whenever they are the least cost
	Remove fossil-fuel subsidies
	Adopt cost-recovery pricing
	Leapfrog to distributed generation, where grid infrastructure does not exist
Middle-income countries	Scale up energy efficiency and renewable energy
	Integrate urban and transport approaches to low carbon use
	Remove fossil-fuel subsidies
	Adopt cost-recovery pricing including local externalities
	Conduct research, development, and demonstration in new technologies
High-income countries	Undertake deep emission cuts at home
	Put a price on carbon: cap-and-trade or carbon tax
	Remove fossil-fuel subsidies
	Increase research, development, and demonstration in new technologies
	Change high-energy-consuming lifestyle
	Provide financing and low-carbon technologies to developing countries

Source: WDR team.

low-carbon technology transfers to developing countries, while pursuing advanced low-carbon technologies and demonstrating that low-carbon growth is feasible (table 4.3).

Acting on all technical and policy fronts

What fundamental changes need to be made in the energy system to narrow the gap between where the world is headed and where it needs to go? The answer lies in a portfolio of efficient and clean energy technologies to reduce energy intensity and shift to low-carbon fuels. On current trends, global energy-related CO_2 emissions will increase from 26 gigatons in 2005 to 43–62 gigatons by 2050.[41] But a 450 ppm CO_2e trajectory requires that energy emissions be reduced to 12–15 gigatons, a 28–48 gigaton mitigation gap by 2050 (figure 4.10). Models rely on four technologies to close this gap—energy efficiency (the largest wedge), followed by renewable energy, carbon capture and storage, and nuclear.[42]

A portfolio of these technologies is needed to achieve the deep emission cuts required by the 450 ppm CO_2e trajectory at least cost, because each has physical and economic constraints, although these vary by country. Energy efficiency faces barriers and market failures. Wind, hydropower, and geothermal power are limited by the availability of suitable sites; biomass is constrained by competition for land and water from food and forests (see chapter 3); and solar is still costly (box 4.5). Nuclear power raises concerns about weapons proliferation, waste management, and reactor safety. Carbon capture and storage technologies for power plants are not yet commercially proven, have high costs, and may be limited by the availability of storage sites in some countries.

Sensitivity analysis incorporating these technology constraints suggests that 450 ppm CO_2e is not achievable without large-scale deployment of energy efficiency, renewable energy, and carbon capture and storage;[43] and that reducing the role of nuclear would require substantial increases of fossil-based carbon capture and storage and renewables.[44] Critical uncertainties include the availability of carbon capture and storage and the development of second-generation biofuels. With today's known

BOX 4.5 *Renewable energy technologies have huge potential but face constraints*

Biomass

Modern biomass as fuel for power, heat, and transport has the highest mitigation potential of all renewable sources.[a] It comes from agriculture and forest residues as well as from energy crops. The biggest challenge in using biomass residues is a long-term reliable supply delivered to the power plant at reasonable costs; the key problems are logistical constraints and the costs of fuel collection. Energy crops, if not managed properly, compete with food production and may have undesirable impacts on food prices (see chapter 3). Biomass production is also sensitive to the physical impacts of a changing climate.

Projections of the future role of biomass are probably overestimated, given the limits to the sustainable biomass supply, unless breakthrough technologies substantially increase productivity. Climate-energy models project that biomass use could increase nearly fourfold to around 150–200 exajoules, almost a quarter of world primary energy in 2050.[b] However, the maximum sustainable technical potential of biomass resources (both residues and energy crops) without disruption of food and forest resources ranges from 80–170 exajoules a year by 2050,[c] and only part of this is realistically and economically feasible. In addition, some climate models rely on biomass-based carbon capture and storage, an unproven technology, to achieve negative emissions and to buy some time during the first half of the century.[d]

Some liquid biofuels such as corn-based ethanol, mainly for transport, may aggravate rather than ameliorate carbon emissions on a life-cycle basis. Second-generation biofuels, based on lignocellulosic feedstocks—such as straw, bagasse, vegetative grass, and wood—hold the promise of sustainable production that is high-yielding and emits low levels of greenhouse gas, but they are still in the R&D stage.

Solar

Solar power, the most abundant energy source on Earth, is the fastest-growing renewable energy industry. Solar power has two major technologies—solar photovoltaic systems and concentrated solar power. Solar photovoltaic systems convert solar energy directly into electricity. Concentrated solar power uses mirrors to focus sunlight on a transfer fluid that generates steam to drive a conventional turbine. Concentrated solar power is much cheaper and offers the greatest potential to produce base-load, large-scale power to replace fossil power plants. But this technology requires water to cool the turbine—a constraint in the desert, where solar plants tend to be installed. So expansion is limited by geography (because concentrated solar power can only use direct beam sunlight) as well as by the lack of transmission infrastructure and large financing requirements. Solar photovoltaics are less location-sensitive, quicker to build, and suitable for both distributed generation and off-grid applications. Solar water heaters can substantially reduce the use of gas or electricity to heat water in buildings. China dominates the global market of solar water heaters, producing more than 60 percent of global capacity.

At current costs, concentrated solar would become cost competitive with coal at a price of $60 to $90 a ton of CO_2.[e] But with learning and economies of scale, concentrated solar power could become cost competitive with coal in less than 10 years, and the global installed capacity could rise to 45–50 gigawatts by 2020.[f] Similarly, solar photovoltaics have a learning rate of 15–20 percent cost reduction with each doubling of installed capacity.[g] Because global capacity is still small, potential cost reductions through learning are substantial.

Wind, hydro, and geothermal

Wind, hydro, and geothermal power are all limited by resources and suitable sites. Wind power has grown at 25 percent a year over the past five years, with installed capacity of 120 gigawatts in 2008. In Europe more wind power was installed in 2008 than any other type of electricity-generating technology. But climate change could affect wind resources, with higher wind speeds but more variable wind patterns.[h]

Hydropower is the leading renewable source of electricity worldwide, accounting for 16 percent of global power. Its potential is limited by availability of suitable sites (global economically exploitable potential of 6 million gigawatt-hours a year),[i] large capital requirements, long lead times to develop, concerns over social and environmental impacts, and climate variability (notably water resources). More than 90 percent of the unexploited economically feasible potential is in developing countries, primarily in Sub-Saharan Africa, South and East Asia, and Latin America.[j] Africa exploits only 8 percent of its hydropower potential.

For many countries in Africa and South Asia, regional hydropower trade could provide the least-cost energy supply with zero carbon emissions. But the lack of political will and trust and concerns about energy security constrain such trade. And greater climate variability will affect the hydrological cycle. Drought or glacial melting could make hydropower supplies unreliable in some regions. Nevertheless, after two decades of stagnation, hydropower is expanding, particularly in Asia. But the current financial crisis makes it more difficult to raise financing to meet the large capital requirements.

Geothermal can provide power, heating, and cooling. It meets 26 percent of Iceland's electricity needs and 87 percent of its building heating demand. But this power source requires major financial commitments in up-front geological investigations and expensive drilling of geothermal wells.

Smart grids and meters

With two-way digital communications between power plants and users, smart grids can balance supply and demand in real time, smooth demand peaks, and make consumers active participants in the production and consumption of electricity. As the share of generation from variable renewable resources such as wind and solar increases, a smart grid can better handle fluctuations in power.[k] It can allow electric vehicles to store power when needed or to sell it back to the grid. Smart meters can communicate with customers, who can then reduce costs by changing appliances or times of use.

Sources:

a. IEA 2008b.

b. IEA 2008b; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; Knopf and others, forthcoming.

c. German Advisory Council on Global Change 2008; Rokityanskiy and others 2006; Wise and others 2009.

d. Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

e. IEA 2008b; Yates, Heller, and Yeung 2009.

f. Yates, Heller, and Yeung 2009.

g. Neij 2007.

h. Pryor, Barthelmie, and Kjellstrom 2005.

i. IEA 2008b.

j. World Bank 2008b.

k. Worldwatch Institute 2009.

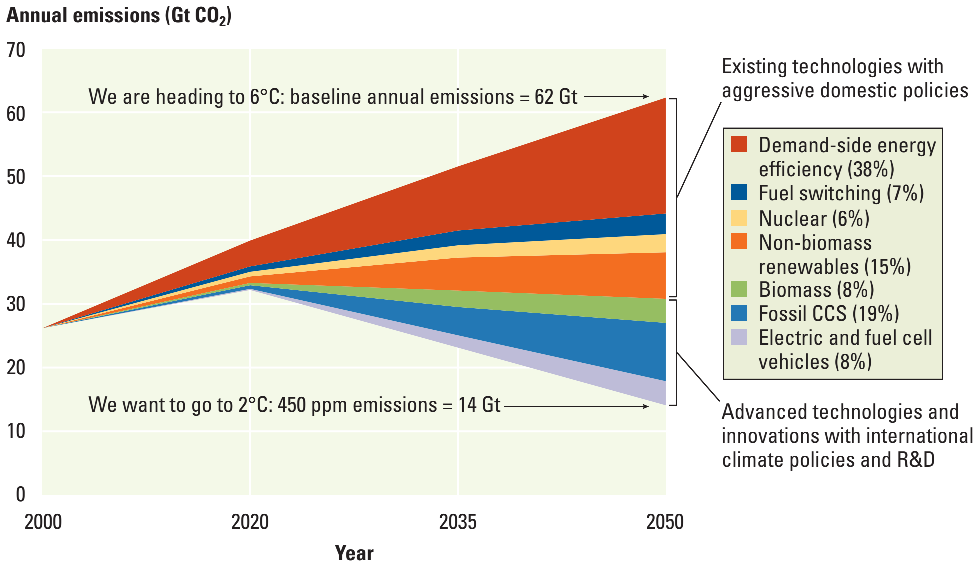
technologies, there is limited room for flexibility in the technology portfolio.

Historically, however, innovation and technology breakthroughs have reduced the costs of overcoming formidable technical barriers, given effective and timely policy action—a key challenge facing the world today. Acid rain and stratospheric ozone depletion are two of many examples demonstrating that estimates of environmental protection costs based on technology extant before regulation are dramatically overstated.[45]

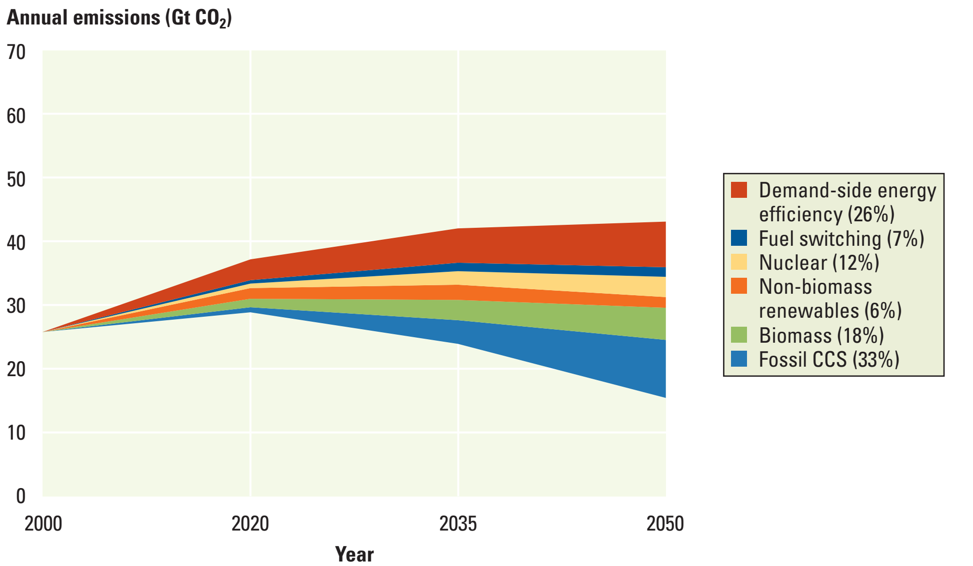
Climate-smart development policies need to be tailored to the maturity of each technology and the national context and can accelerate the development and deployment of these technologies (figure 4.11 and table 4.4).

Figure 4.10 The emissions gap between where the world is headed and where it needs to go is huge, but a portfolio of clean energy technologies can help the world stay at 450 ppm CO_2e (2°C)

a. CO_2 emissions from the energy sector: wedge analysis for IEA Blue Scenario (450 ppm CO_2e)



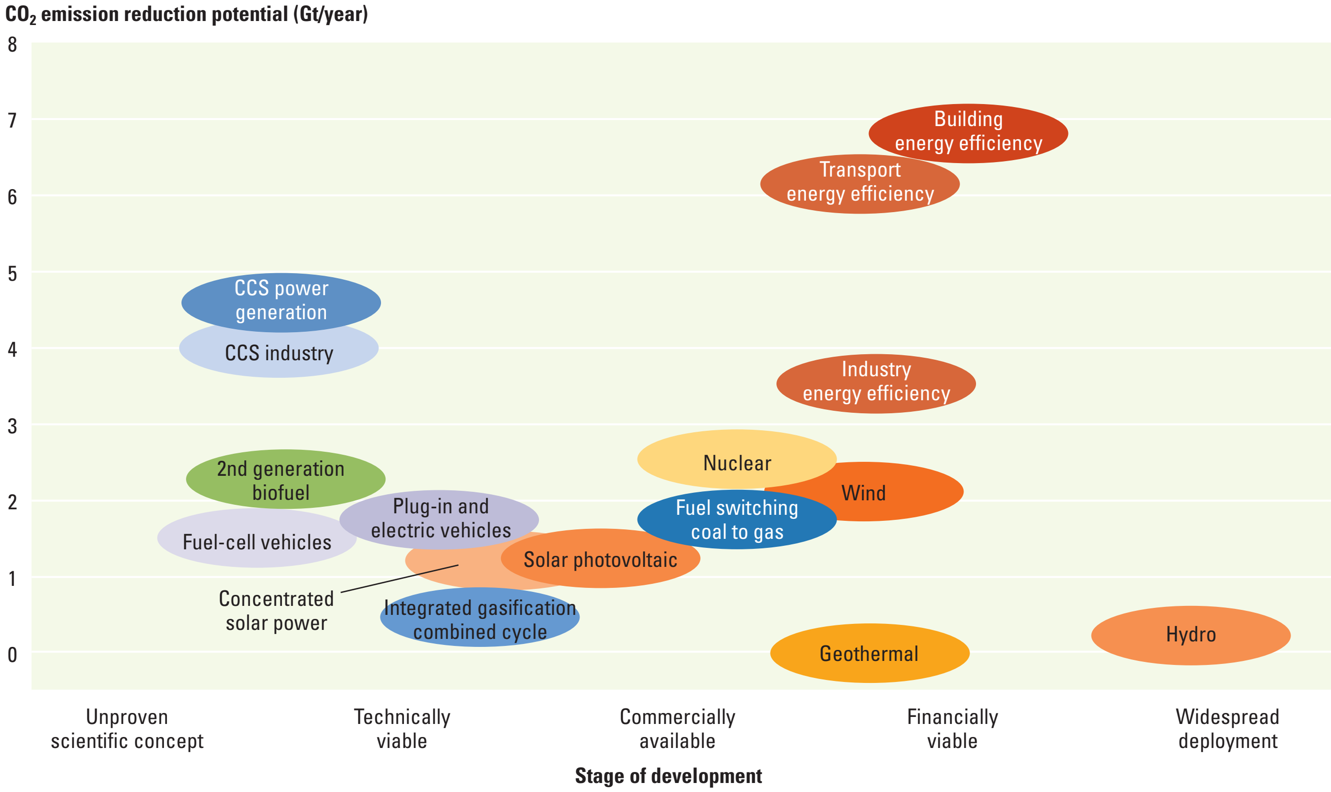
b. CO_2 emissions from the energy sector: wedge analysis for MESSAGE B2 (450 ppm CO_2e)



Sources: WDR team, based on data from Riahi, Grübler, and Nakićenović 2007; IIASA 2009; IEA 2008b.

Note: Fuel switching is changing from coal to gas. Non-biomass renewables include solar, wind, hydropower, and geothermal. Fossil CCS is fossil fuels with carbon capture and storage. While the exact mitigation potential of each wedge may vary under different models depending on the baseline, the overall conclusions remain the same.

Figure 4.11 The goal is to push low-carbon technologies from unproven concept to widespread deployment and to higher emission reductions



Source: WDR team, based on data from World Bank 2008a and IEA 2008a (mitigation potential from IEA Blue Scenario in 2050).

Note: See table 4.4 for detailed definitions of technology development stage. A given technology group can be progressing through different stages at the same time but in different country settings and at different scales. Wind, for example, is already cost competitive with gas-fired power plants in most of the United States (Wiser and Bolinger 2008). But in China and India wind may be economically but not financially viable against coal-fired power plants. So for clean technologies to be adopted in more places and at larger scales, they must move from the top to bottom in table 4.4.

Table 4.4 Policy instruments tailored to the maturity of technologies

Maturity level	Status	Issues to address to move to next stage	Policy support
Technically viable	The basic science is proven and tested in the lab or on a limited scale. Some technical and cost barriers remain.	Development and demonstration to prove operational viability at scale and to minimize costs. Internalize global externalities.	Technology development policies: Substantial public and private R&D, and large-scale demonstration. Internalize global externalities through carbon tax or cap-and-trade. Technology transfer.
Commercially available and economically viable	The technology is available from commercial vendors. Projected costs are well understood. Technology is economically viable, justified by country's development benefits. But it cannot yet compete against fossil fuels without subsidy and/or internalization of local externality.	Leveling the playing field between clean energy and fossil fuels.	Domestic policies to provide a level playing field: Remove fossil-fuel subsidies and internalize local externalities. Provide financial incentives for clean energy technologies.
Financially viable	Technology is financially viable for project investors—cost competitive with fossil fuels, or has high financial returns and short payback period for demand options.	Market failures and barriers hamper accelerating adoption through the market.	Regulations, with financial incentives to remove market failures and barriers. Support for delivery mechanisms and financing programs to expand adoption. Consumer education.
Widespread	Technology is being adopted widely through market operation.		

Source: WDR team.

Energy efficiency. In the short term the largest and cheapest source of emission reductions is increased energy efficiency on both the supply and demand side in power, industry, buildings, and transport. Well-established technologies offer near-term reductions in greenhouse gas emissions by capturing methane emissions[46] from coal mines, municipal solid wastes, and gas flaring and by reducing black carbon emissions from traditional biomass fuels. These technologies can also enhance coal mine safety and improve public health by reducing air pollution.[47] Many energy-efficiency measures are financially viable for investors but are not fully realized. Realizing these low-cost savings requires regulations such as efficiency standards and codes—combined with financial incentives, institutional reforms, financing mechanisms, and consumer education—to correct market failures and barriers.

Existing supply-side low-carbon technologies. In the short to medium term, low- or zero-emission fuels for the power sector—renewable energy and nuclear power—are commercially available and could be deployed much more widely under the right policy and regulatory frameworks. Smart and robust grids can enhance the reliability of electric networks and minimize the downside of relying on variable renewable energy and distributed generation (see box 4.5). Fuel switching from coal to natural gas also has great mitigation potential but increases energy security risks for gas-importing countries. Most renewable energy technologies are economically viable but not yet financially viable, so some form of subsidy (to internalize the externalities) is needed to make them cost competitive with fossil fuels. Adopting these technologies on a larger scale will require that fossil-fuel prices reflect the full cost of production and externalities, plus financial incentives to adopt low-carbon technologies.

Advanced technologies. While commercially available technologies can provide a substantial share of the abatement needed in the short to medium term,[48] limiting warming to 2°C requires developing and deploying advanced technologies (carbon capture and storage in power and industry, second-generation biofuels, and electric vehicles) at unprecedented scale and speed (box 4.6). Policies that put an adequate price on carbon are essential, as are international efforts to transfer low-carbon technologies to developing countries. Given the long lead time for technology development and the early emission peaking date required to limit temperature increases to 2°C, governments need to ramp up research, development, and demonstration efforts now to accelerate the innovation and deployment of advanced technologies. Developed countries will need to take the lead in making these technologies a reality.

An integrated systems approach is needed to ensure compatible policies for sector-wide and economywide emission reductions. Market-based mechanisms, such as a carbon cap-and-trade system or a carbon tax (see chapter 6), encourage the private sector to invest in least-cost, low-carbon technologies to achieve deep emission cuts.

Integrated urban and transport approaches combine urban planning, public transport, energy-efficient buildings, distributed generation from renewable sources, and clean vehicles (box 4.7). Latin America's pioneering experiences with rapid bus transit—dedicated bus lanes, prepayment of bus fares, and efficient intermodal connections—are examples of a broader urban transformation.[49] Modal shifts to mass transit have large development co-benefits of time savings in traffic, less congestion, and better public health from reduced local air pollution.

Changing behaviors and lifestyles to achieve low-carbon societies will take a concerted educational effort over many years. But by reducing travel, heating, cooling, and appliance use and by shifting to mass transit, lifestyle changes could reduce annual CO_2 emissions by 3.5–5.0 gigatons by 2030—8 percent of the reduction needed (see chapter 8).[50]

Governments do not have to wait for a global climate deal—they can adopt domestic efficient and clean energy policies now, justified by development and financial co-benefits. Such domestic win-win measures

BOX 4.6 *Advanced technologies*

Carbon capture and storage (CCS) could reduce emissions from fossil fuels by 85–95 percent and is critical in sustaining an important role for fossil fuels in a carbon-constrained world. It involves three main steps:

- CO_2 capture from large stationary sources, such as power plants or other industrial processes, before or after combustion.
- Transport to storage sites by pipelines.
- Storage through injection of CO_2 into geological sites, including: depleted oil and gas fields to enhance oil and gas recovery, coal beds to enhance coal bed methane recovery, deep saline formations, and oceans.

Currently, CCS is competitive with conventional coal only at a price of $50 to $90 a ton of CO_2.[a] Still at the R&D stage, it is technologically immature. The number of economically available geological sites close to carbon emission sources varies widely from country to country. Early opportunities to lower costs are at depleted oil fields and enhanced oil recovery sites, but storage in deep saline aquifers would also be required for deep emission cuts. CCS also significantly reduces efficiency of power plants and has the potential for leakage.

The near-term priority should be spurring large-scale demonstration projects to reduce costs and improve reliability. Four large-scale commercial CCS demonstration projects are in operation—in Sleipner (Norway); Weyburn (Canada-United States); Salah (Algeria); and Snohvit (Norway)—mostly from gas or coal gasification. Together these projects capture 4 million tons of CO_2 per year. A 450 ppm CO_2e trajectory requires 30 large-scale demonstration plants by 2020.[b] Capturing CO_2 from low-efficiency power plants is not economically viable, so new power plants should be built with highly efficient technologies for retrofitting with CCS later. Legal and regulatory frameworks must be established for CO_2 injection and to address long-term liabilities. The European Union has adopted a directive on the geological storage of CO_2, and the United States has proposed CCS rules. Detailed assessments of potential carbon storage sites are also needed, particularly in developing countries. Without a massive international effort, resolving the entire chain of technical, legal, institutional, financial, and environmental issues could require a decade or more before applications go to scale.

Plug-in hybrids offer a potential near-term option as a means of transition to full electric vehicles.[c] They combine batteries with smaller internal combustion engines, which allow them to travel part-time on electricity provided by the grid through recharging at night. When running on electricity generated from renewable energy, they emit 65 percent less CO_2 than a gasoline-powered car.[d] However, they increase electricity consumption, and the net emission reductions depend on the electricity source. Significant improvements and cost reductions in energy storage technology are required. Electric vehicles are solely battery-powered, but they require much greater battery capacity than plug-in hybrids and are more expensive.

Sources:
a. IEA 2008b.
b. IEA 2008b.
c. IEA 2008b.
d. NRDC 2007.

can go a long way to close the mitigation gap,[51] but they must be supplemented with international climate agreements to bridge the remaining gap.

Realizing the savings from energy efficiency

Globally an additional dollar invested in energy efficiency avoids more than two dollars in investment on the supply side, and the payoffs are even higher in developing countries.[52] So energy efficiency (*nega*watts) should be considered on a par with traditional supply-side measures (megawatts) in energy resource planning. Energy efficiency reduces energy bills for consumers, increases the competitiveness of industries, and creates jobs. Energy efficiency is essential for the 2°C trajectory, because it buys time by delaying the need to build additional capacity while advanced clean energy technologies are being developed and brought to market.

Buildings consume nearly 40 percent of the world's final energy,[53] about half for heating space and water, and the rest for running electric appliances, including lighting, air conditioning, and refrigeration.[54] Opportunities to improve energy efficiency lie in the building envelope (roof, walls, windows, doors, and insulation), in space and water heating, and in appliances. Buildings present one of the most cost-effective mitigation options, with more than 90 percent of potential mitigation achievable with a CO_2 price of less than $20 a ton.[55] Studies find that existing energy-efficiency technologies can cost-effectively save 30 to 40 percent of energy use in new buildings, when evaluated on a life-cycle basis.[56]

While most of these studies are based on high-income country data, the potential for energy-efficiency savings in developing countries can be larger because of the low baseline. For example, the current space-

BOX 4.7 *The role for urban policy in achieving mitigation and development co-benefits*

Urbanization is often cited as a major driver of global emissions growth[a] but is better understood as a major driver of development.[b] It is therefore a crucial nexus of climate and development policy making. Most emissions occur in cities precisely because that is where most production and consumption occur. And the high concentration of population and economic activity in cities can actually increase efficiency—if the right policies are in place. A number of factors call for an urban climate agenda.

First, denser cities are more energy and emission efficient (for example, in the transport sector; see the figure below), and local policies are essential for encouraging densification.[c] Second, the strong and persistent influence of infrastructure on long-term residential and commercial citing decisions reduces the responsiveness of emissions to price signals. Complementary regulation and land-use planning are therefore needed. Third, the interdependence of the systems that constitute the urban form—roads and public transit lines; water, wastewater, and power services; and residential, commercial, and industrial buildings—and that are not easily changed once the initial patterns are set, increases the urgency of designing low-emissions cities in rapidly urbanizing countries.

As discussed in chapter 8, cities have already become a source of political momentum and will advance mitigation actions on the international stage even as they pursue their own initiatives at home. Contrary to a general presumption that local decision making focuses on local issues, more than 900 U.S. cities have signed on to meet or exceed Kyoto Protocol targets to reduce greenhouse gas emissions,[d] while the C40 Cities Climate Leadership Group that aims to promote action to combat climate change includes major cities on all continents.[e]

Cities have the unique ability to respond to a global issue like climate change at a tangible local level. Many cities have legislated to limit the use of plastic bags, disposable cups, or bottled water. These initiatives may be important for social messaging, but their environmental impact has so far been minimal. Deeper, higher-impact efforts—such as congestion charging, green building incentives, support for urban design requiring less automobile dependence, and incorporation of carbon pricing in land taxes and development rights—will ultimately require a more comprehensive cultural momentum to overcome entrenched (or aspirational) high-carbon lifestyle preferences. Fortunately, many city-led measures needed for mitigation have benefits for adaptation to climate change, which will reduce tradeoffs.

Sources: WDR team.
a. Dodman 2009.
b. World Bank 2008f.
c. World Bank 2009b.
d. U.S. Conference of Mayors Climate Change Protection Agreement.
e. See http://www.c40cities.org/. In addition, the United Cities and Local Governments and International Council for Local Environmental Initiatives have a joint resolution requesting a greater voice for cities in the UNFCCC negotiating process.

Emissions from transport are much lower in denser cities

Source: World Bank 2009b.
Note: The figure does not correct for income because a regression of transport emissions on density and income reveals that density, not income, is a key factor. Data are for 1995.

heating technology used in Chinese buildings consumes 50 to 100 percent more energy than that used in Western Europe. Making buildings in China more energy efficient would add 10 percent to construction costs but would save more than 50 percent on energy costs.[57] Technology innovations such as advanced building materials can further increase the potential energy savings (see chapter 7). Integrated zero-emission building designs, combining energy-efficiency measures with on-site power and heat from solar and biomass, are technically and economically feasible—and the costs are falling.[58]

Manufacturing accounts for one-third of global energy use, and the potential for energy savings in industry is particularly large in developing countries. Key opportunities include improving the efficiency of energy-intensive equipment such as motors and boilers and of energy-intensive industries such as iron, steel, cement, chemicals, and petrochemicals. One of the most cost-effective measures is combined heat and power. Existing technologies and best practices could reduce energy consumption in the industrial sector by 20–25 percent, helping reduce carbon footprints without sacrificing growth.[59] In Mexico cogeneration in the refineries of Pemex, the large state-owned petroleum company, could provide more than 6 percent of the country's installed power capacity at a negative mitigation cost (meaning that the sale of previously wasted electricity and heat would generate sufficient revenue to more than offset the required investments).[60]

Improving vehicle fuel efficiency, for example by shifting to hybrid cars, is the most cost-effective means of cutting emissions in the transport sector in the near to medium term. Improving power-train systems (for example, by downsizing conventional internal combustion engines) and making other design changes, such as lower vehicle weight, optimized transmissions, and start-stop systems with regenerative braking, can also improve fuel efficiency.

In addition, smart urban planning—denser, more spatially compact, and with mixed-use urban design that allows growth near city centers and transit corridors to prevent urban sprawl—can substantially reduce energy demand and CO_2 emissions. It reduces the vehicle kilometers traveled and makes it possible to rely on district and integrated energy systems for heating.[61] In Mexico, for example, dense urban development is expected to reduce total emissions by 117 million tons of CO_2e from 2009 to 2030, with additional social and environmental benefits.[62]

Market and nonmarket barriers and failures

The large untapped potential for greater energy efficiency demonstrates that low-cost energy savings are not easy. Small-scale, fragmented energy-efficiency measures, involving multiple stakeholders and tens of millions of individual decision makers, are fundamentally more complex than large-scale, supply-side options. Energy-efficiency investments need cash up front, but future savings are less tangible, making such investment risky compared with asset-based energy-supply deals. Many market failures and barriers, as well as nonmarket barriers, to energy efficiency exist and tackling them requires policies and interventions that entail additional costs (box 4.8). Another concern is the rebound effect: acquiring efficient equipment lowers energy bills, so consumers tend to increase energy consumption, eroding some of the energy reductions. But empirically the rebound is small to moderate, with long-run effects of 10–30 percent for personal transport and space heating and cooling,[63] and these can be mitigated with price signals.

Price should reflect true cost

Many countries channel public subsidies, implicit and explicit, to fossil fuels, distorting investment decisions for clean energy. Energy subsidies in the 20 highest-subsidizing developing countries are estimated at around \$310 billion a year, or around 0.7 percent of world GDP in 2007.[64] The lion's share of the subsidies artificially lowers the prices of fossil fuels, providing disincentives to save energy and making clean energy less attractive financially.[65]

Removing fossil-fuel subsidies would reduce energy demand, encourage the supply of clean energy, and lower CO_2 emissions.

BOX 4.8 *Energy efficiency faces many market and nonmarket barriers and failures*

- *Low or underpriced energy*. Low energy prices undermine incentives to save energy.
- *Regulatory failures*. Consumers who receive unmetered heat lack the incentive to adjust temperatures, and utility rate-setting can reward inefficiency.
- *A lack of institutional champion and weak institutional capacity*. Energy-efficiency measures are fragmented. Without an institutional champion to coordinate and promote energy efficiency, it becomes nobody's priority. Moreover, there are few energy-efficiency service providers, and their capacity will not be established overnight.
- *Absent or misplaced incentives*. Utilities make a profit by generating and selling more electricity, not by saving energy. For most consumers, the cost of energy is small relative to other expenditures. Because tenants typically pay energy bills, landlords have little or no incentive to spend on efficient appliances or insulation.
- *Consumer preferences*. Consumer decisions to purchase vehicles are usually based on size, speed, and appearance rather than on efficiency.
- *Higher up-front costs*. Many efficient products have higher up-front costs. Individual consumers usually demand very short payback times and are unwilling to pay higher up-front costs. Preferences aside, low-income customers may not be able to afford efficient products.
- *Financing barriers and high transaction costs*. Many energy-efficiency projects have difficulty obtaining financing. Financial institutions usually are not familiar with or interested in energy efficiency, because of the small size of the deal, high transaction costs, and high perceived risks. Many energy service companies lack collateral.
- *Products unavailable*. Some efficient equipment is readily available in high- and middle-income countries but not in low-income countries, where high import tariffs reduce affordability.
- *Limited awareness and information*. Consumers have limited information on energy-efficiency costs, benefits, and technologies. Firms are unwilling to pay for energy audits that would inform them of potential savings.

Source: WDR team.

Ample evidence shows that higher energy prices induce substantially lower demand.[66] If Europe had followed the U.S. policy of low fuel taxes, its fuel consumption would be twice as large as it is now.[67] Removing fossil-fuel subsidies in power and industry could reduce global CO_2 emissions by as much as 6 percent a year and add to global GDP.[68]

But removing those subsidies is no simple matter—it requires strong political will. Fuel subsidies are often justified as protecting poor people, even though most of the subsidies go to better-off consumers. As chapters 1 and 2 discuss, effective social protection targeted at low-income groups, in conjunction with the phased removal of fossil-fuel subsidies, can make reform politically viable and socially acceptable. It is also important to increase transparency in the energy sector by requiring service companies to share key information, so that the governments and other stakeholders can make better-informed decisions and assessments about removing subsidies.

Energy prices should reflect the cost of production and incorporate local and global environmental externalities. Urban air pollution from fossil-fuel combustion increases health risks and causes premature deaths. Lower-respiratory disease resulting from air pollution is a top cause of mortality in low-income countries and a leading contributor to the global burden of disease.[69] A 15 percent greenhouse gas reduction below business as usual by 2020 in China would result in 125,000–185,000 fewer premature deaths annually from pollution emitted by power generation and household energy use.[70] Pricing local air pollution can be very effective in reducing the related health costs.

Pricing carbon, through a carbon tax or cap-and-trade system (see chapter 6), is fundamental to scaling up advanced clean energy technologies and leveling the playing field with fossil fuels.[71] It provides incentives and reduces risks for private investments and innovations in efficient and clean energy technologies on a large scale (see chapter 7).[72] Developed countries should take the lead in pricing carbon. Legitimate concerns include protecting the poor from high energy prices and compensating the losing industries, particularly in developing countries. Social safety nets and nondistortionary income support, possibly from revenues generated by the carbon tax or permit auction, can help (see chapters 1 and 2).

Pricing policy alone is not enough; energy-efficiency policies are also critical

Carbon-pricing policies alone will not be enough to ensure large-scale development and deployment of energy efficiency and low-carbon technologies (box 4.9). Energy efficiency faces distinct barriers in different sectors. For power, where a small number of decision makers determine whether energy-efficiency measures are adopted, financial incentives are likely to be effective. For transport, buildings, and industry—where adoption is a function of the preferences of, and requires action by, many decentralized individuals—energy demand is less responsive to price signals, and regulations tend to be more effective. A suite of policy instruments can replicate proven successes in removing barriers to energy efficiency.

BOX 4.9 *Carbon pricing alone is not enough*

Carbon pricing alone cannot guarantee large-scale deployment of efficient and clean energy, because it cannot fully overcome the market failures and nonmarket barriers to the innovation and diffusion of low-carbon technologies.[a]

First, price addresses only one of many barriers. Others, such as a lack of institutional capacity and financing, block the provision of energy-saving services.

Second, while the price elasticity of energy demand is high over the long term, it is generally quite inelastic in the short term, because people have few short-run options for reducing their transport needs and household energy use in response to fuel price changes. Automobile fuel prices have an historical short-term elasticity ranging from only −0.2 to −0.4,[b] with a much smaller response of −0.03 to −0.08 in recent years,[c] but a long-term elasticity ranging between −0.6 and −1.1.

Third, the low price elasticity of adoptiing many energy-efficiency measures may also be a result of high opportunity costs in rapidly growing developing countries like China. A return of 20 percent for an efficiency measure is attractive, but investors may not invest in efficiency if other investments with equivalent risks have higher returns.

So, strong pricing policies are important but not enough. They need to be combined with regulations to correct market failures, remove market and nonmarket barriers, and foster clean technology development.

Sources:
a. ETAAC 2008.
b. Chamon, Mauro, and Okawa 2008.
c. Hughes, Knittel, and Sperling 2008.

Regulations. Economywide energy-intensity targets, appliance standards, building codes, industry performance targets (energy consumption per unit of output), and fuel-efficiency standards are among the most cost-effective measures. More than 35 countries have national energy-efficiency targets. France and the United Kingdom have gone a step further in energy-efficiency obligations by mandating that energy companies meet energy-saving quotas. In Japan energy-efficiency performance standards require utilities to achieve electricity savings equal to a set percentage of their baseline sales or load.[73] Brazil, China, and India have energy-efficiency laws, but as in all contexts, effectiveness depends on enforcement. Other options include the mandatory phasing out of incandescent lights.

Complying with efficiency standards can avoid or postpone adding new power plant capacity and reduce consumer prices. And industrial energy performance targets can spur innovation and increase competitiveness. For new buildings in Europe the cumulative energy savings from building codes is about 60 percent over those built before the first oil shock in the 1970s.[74] Refrigerator efficiency standards in the United States have saved 150 gigawatts in peak power demand over the past 30 years, more than the installed capacity of the entire U.S. nuclear program.[75] Efficiency standards and labeling programs cost about 1.5 cents a kilowatt-hour, much cheaper than any electricity supply option.[76] The average price of refrigerators in America has fallen by more than half since the 1970s, even as their efficiency has increased by three-quarters.[77]

Financial incentives. In many developing countries weak enforcement of regulations is a concern. Regulations need to be supplemented with financial incentives for consumers and producers. Low-income consumers are most sensitive to the higher up-front costs of efficient products. Financial incentives to offset these up-front costs, such as consumer rebates and energy-efficient mortgages,[78] can change consumer behavior, increase affordability, and overcome barriers to market entry by new, efficient producers. In addition, regulations are also vulnerable to rebound effects, so pricing policies are needed to discourage consumption. Fuel taxes have proved one of the most cost-effective ways to reduce transport energy demand, along with congestion charges and insurance or tax levies on vehicles based on kilometers traveled, and higher taxes on light trucks and sports utility vehicles (table 4.5).

Utility demand-side management has produced large energy savings. Key to success is decoupling utility profits from electricity sales to give utilities incentives to save. Regulators forecast demand and allow utilities to charge a price that would recoup their costs and earn a fixed return based on that forecast. If demand turns out to be lower than expected, the regulator lets prices rise so that the utility can make the mandated profit; if it is higher, the regulator cuts prices to return the excess to customers (box 4.10).

Institutional reform. An institutional champion, such as a dedicated energy-efficiency agency, is essential to coordinate multiple stakeholders and promote and manage energy-efficiency programs. More than 50 countries, developed and developing, have a national energy-efficiency agency. It can be a government agency with a focus on clean energy or energy efficiency (the most common), such as the Department of Alternative Energy Development and Efficiency in Thailand, or an independent corporation or authority, such as the Korea Energy Management Corporation. To achieve successful results, they require adequate resources, the ability to engage multiple stakeholders, independence in decision making, and credible monitoring of results.[79]

Energy service companies (ESCOs) provide energy-efficiency services such as

Table 4.5 Policy interventions for energy efficiency, renewable energy, and transport

Policy area	Energy efficiency and demand-side management interventions	Renewable energy interventions	Barriers addressed
Economywide	Removal of fossil-fuel subsidies Tax (fuel or carbon tax) Quantitative limits (cap-and-trade)		Environmental externalities not included in the price Regressive or demand-augmenting distortions from subsidies for fossil fuels
Regulations	Economywide energy-efficiency targets Energy-efficiency obligations Appliance standards Building codes Industry energy-performance targets Fuel economy standards	Mandatory purchase, open and fair grid access Renewable portfolio standards Low-carbon fuel standards Technology standards Interconnection regulations	Lack of legal framework for renewable independent power producers Lack of transmission access by renewable energy Lack of incentives and misplaced incentives to save Supply-driven mentality Unclear interconnection requirements
Financial incentives	Tax credits Capital subsidies Profits decoupled from sales Consumer rebates Time-of-use tariffs Fuel taxes Congestion tolls Taxes based on engine size Insurance or tax levies on vehicle miles traveled Taxes on light trucks, SUVs	Feed-in tariff, net metering Green certificates Real-time pricing Tax credits Capital subsidies	High capital costs Unfavorable pricing rules Lack of incentives for utilities and consumers to save
Institutional arrangements	Utility Dedicated energy-efficiency agencies Independent corporation or authority Energy service companies (ESCOs)	Utility Independent power producers	Too many decentralized players
Financing mechanisms	Loan financing and partial loan guarantees ESCOs Utility energy-efficiency, demand-side management program, including system benefit fund	System benefit fund Risk management and long-term financing Concessional loans	High capital cost, and mismatch with short-term loans ESCOs' lack of collateral and small deal size Perceived high risks High transaction costs Lack of experience and knowledge
Promotion and education	Labeling Installing meters Consumer education	Education about renewable energy benefits	Lack of information and awareness Loss of amenities

Source: WDR team.

BOX 4.10 *California's energy-efficiency and renewable energy programs*

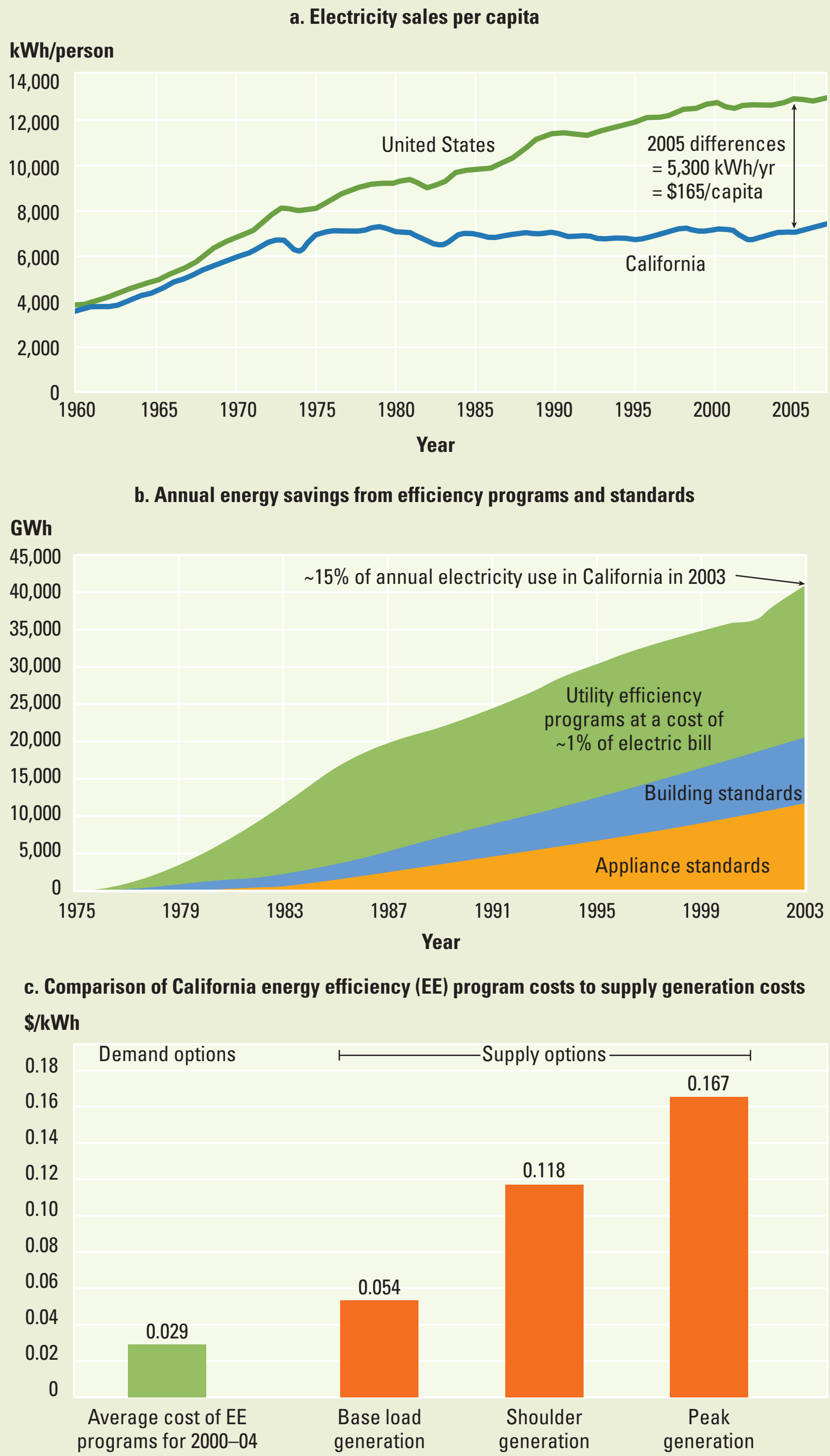
A U.S. leader in energy efficiency, California has kept its electricity consumption per capita flat for the past 30 years, substantially below the U.S. national average (figure, panel a). Appliance standards and building codes, along with financial incentives for utility demand-side management programs, are estimated to be responsible for one-quarter of the difference (figure, panel b). California decoupled utility profits from sales in 1982 and recently went a step further with "decoupling-plus"—utilities earn additional money if they meet or exceed savings goals.

The state's energy-efficiency program has an annual budget of $800 million, collected from tariff surcharges on electricity and used for utility procurements, demand-side management, and research and development. The average cost of the program is about 3 cents per kilowatt-hour, far lower than the cost of supply (figure, panel c). To promote renewable energy, the state is implementing renewable portfolio standards to increase renewable energy's share in power generation to 20 percent by 2010.

In June 2005 California became the first U.S. state to issue an executive order on climate change, setting a target for reducing greenhouse gas emissions to the 2000 level by 2010, to the 1990 level by 2020, and to 80 percent below the 1990 level by 2050. Energy efficiency is projected to contribute about 50 percent of this reduction.

Sources: California Energy Commission 2007a; Rosenfeld 2007; Rogers, Messenger, and Bender 2005; Sudarshan and Sweeney, forthcoming.

California's electricity consumption per capita has remained flat over the past 30 years, thanks largely to utility demand-side management and efficiency standards. The cost of energy efficiency is much lower than that of electricity supply



energy auditing, recommend energy saving measures, and provide financing to clients; they also serve as project aggregators. Most ESCOs have had difficulty in obtaining adequate financing from commercial banks because of their weak balance sheets and the perceived higher risks of loans dependent on revenues from energy savings. Policies, financing, and technical support from governments and international development banks can strengthen ESCOs and mainstream their business model. In China, for example, after a decade of capacity building supported by the World Bank, the ESCO industry grew from three companies in 1997 to more than 400, with $1 billion in energy performance contracts in 2007.[80]

Financing mechanisms. Developing and operating energy-efficiency services for investment in energy efficiency are primarily institutional issues. Lack of domestic capital is rarely a problem, but inadequate organizational and institutional systems for developing projects and accessing funds can be barriers to finance. The three main financing mechanisms for energy-efficiency projects are ESCOs, utility demand-management programs, and loan financing and partial loan guarantee schemes operating within commercial banks, as specialized agencies, or as revolving funds.[81]

Lending through local commercial banks offers the best prospect for program sustainability and maximum impact. International financial institutions have supported partial-risk-guarantee programs to mitigate the risks of energy-efficiency projects for commercial banks, increasing the banks' confidence in jump-starting energy-efficiency financing (box 4.11). Dedicated revolving funds are another common approach, particularly in countries where investing in energy efficiency is in the early stages and banks are not ready to provide financing.[82] This approach is transitional, and sustainability is a major issue.

Utility demand-side management is usually funded through a system benefit fund (financed by a tariff surcharge on kilowatt-hours to all electricity customers), which is more sustainable than government budgets. Administered by either utilities or dedicated energy-efficiency agencies, the funds cover incremental costs of switching to renewable energy from fossil fuels, consumer rebates, concessional loans, research and development, consumer education, and low-income consumer assistance.

Public procurement. Mass procurement of energy-efficient products can substantially reduce costs, attract larger contracts and bank lending, and lower transaction costs. In Uganda and Vietnam the bulk procurement of 1 million compact fluorescent lamps in each country substantially reduced the cost of the lamps and improved product quality through technical specifications and warranty; once installed, they cut peak demand by 30 megawatts.[83] Public procurement through government agencies, usually one of the biggest energy consumers in an economy, can reduce costs and demonstrate government's commitment and to leadership in energy efficiency. But mandates, incentives, and procurement and budgeting rules have to be in place.[84]

Consumer education. Consumer education can promote lifestyle changes and more informed choices—examples include energy-efficiency labeling and increased use of elec-

BOX 4.11 *World Bank Group experience with financing energy efficiency*

The World Bank and the International Finance Corporation (IFC) have financed a series of energy-efficiency financial intermediary projects, mostly in Eastern Europe and East Asia. The IFC pioneered the use of a guarantee mechanism through selected domestic banks with the Hungary Energy Efficiency Guarantee Fund. A Global Environment Facility grant of $17 million was used to guarantee $93 million worth of loans for energy-efficient investments. No guarantee has been called, giving local banks confidence in and familiarity with energy-efficiency lending.

One of the key lessons of the experience is the importance of technical assistance, particularly at the beginning, to raise awareness of energy efficiency, to provide training and advisory services to the banks in developing financial mechanisms, and to build the capacity of project developers. While in Bulgaria the transaction cost of institutional capacity building for both financial institutions and energy service companies—from project concept to financial closure—has been around 10 percent of total project costs at the beginning, it is expected to decline to around 5–6 percent later on.

Sources: WDR team; Taylor and others 2008.

tricity and heat meters, particularly smart meters. Consumer awareness campaigns are most effective in conjunction with regulations and financial incentives. Based on experience in the public health field, interventions to change behaviors need to occur at multiple levels—policy, physical environment (design of walkable cities and green buildings), sociocultural (media communications), interpersonal (face-to-face contacts), and individual (see chapter 8).[85]

Scaling up existing low-carbon technologies

Renewable energy could contribute around 50 percent to the power mix by 2050.[86] With costs of renewable energy declining over the past two decades, wind, geothermal, and hydro power are already or nearly cost-competitive with fossil fuels.[87] Solar is still costly, but costs are expected to decline rapidly along the learning curve over the next few years (box 4.12). With rising fossil-fuel prices, the cost gap is closing. Biomass, geothermal power, and hydropower can provide base-load power, but solar and wind are intermittent.

A large share of intermittent resources in the grid system may affect reliability, but this can be addressed in a variety of ways—through hydropower or pumped storage, load management, energy storage facilities, interconnection with other countries, and smart grids.[88] Smart grids can enhance

BOX 4.12 *Difficulties in comparing energy technology costs: A matter of assumptions*

Comparing costs of different energy technologies is a tricky business. A frequently used approach for comparing electricity generation technologies is based on costs per kilowatt-hour (kWh). A levelized-cost method is commonly used to compare the life-cycle economic costs of energy alternatives that deliver the same energy services. First, capital costs are calculated using a simple capital recovery factor method.[a] This method divides the capital cost into an equal payment series—an annualized capital cost—over the lifetime of the equipment. Then the annualized capital costs are added to the annual operation and maintenance (O&M) costs and the fuel costs to obtain the levelized costs. So capital costs, O&M costs, fuel costs, the discount rate, and a capacity factor are key determinants of levelized costs.

In reality, costs are time and site specific. The costs of renewable energy are closely linked to local resources and sites. Wind costs, for example, vary widely depending on site-specific wind resources. Labor costs and construction time are also key factors, particularly for fossil-fuel and nuclear plants. Chinese coal-fired power plants, for example, cost about one-third to one-half of the international prices for similar plants. The long lead time to construct nuclear power plants contributes to the high costs in the United States.

Second, sensible integrated comparative assessment of different energy technologies compares all the economic attributes along the primary fuel cycle for a unit of energy benefits. Comparing renewable energy costs with fossil fuel and nuclear should take into account the different services they provide (base-load or intermittent energy). On the one hand, solar and wind energy produce variable outputs, although outputs can be enhanced in various ways, usually at an additional cost. On the other hand, solar and wind energy technologies can typically be licensed and built in much less time than large-scale fossil or nuclear plants.

Third, externalities such as environmental costs and portfolio diversification values should be incorporated when comparing fossil-fuel costs and clean energy costs. A carbon price will make a big difference in pushing up the costs of fossil fuels. Fossil-fuel price volatility creates additional negative externalities. Increasing fuel prices by 20 percent increases the costs of generation by 16 percent for gas and 6 percent for coal, while leaving renewable energy practically untouched. Adding renewable energy sources provides portfolio diversification value because it hedges against the volatility of fossil fuel prices and supplies. Including this portfolio diversification value in the evaulation of renewables increases their attractiveness.[b]

When dealing with new technologies, the potential for cost reduction should also be factored in. Dynamic analysis of future costs of new technologies depends on the assumptions made about the learning rate—the cost reductions associated with a doubling of capacity. The cost of wind energy has dropped nearly 80 percent over the past 20 years. Technology breakthroughs and economies of scale can lead to more rapid cost reductions, a phenomenon some experts now expect will lead to dramatic near-term reductions in solar cell prices.[c]

In financial analysis, differences in institutional context (whether public or private financing) and government policies (taxes and regulations) are often the deciding factors. Differences in financing costs are particularly important for the most capital-intensive technologies like wind, solar, and nuclear. A California study shows that the cost of a wind power plant varies much more than the cost of a gas combined cycle plant, with different financing terms for private ("merchant"), investor-owned, and publicly owned utilities.[d]

Sources:

a. The capital recovery factor = $[i(1+i)^n]/[(1+i)^n - 1]$ where i is the discount rate and n is the lifetime or period of capital recovery of the systems.

b. World Economic Forum 2009.

c. Deutsche Bank Advisors 2008 (projected photovoltaic cost reductions).

d. California Energy Commission 2007b.

reliability of electricity networks when incorporating variable renewable energy and distributed generation. High-voltage, direct-current lines can make long-range transmission possible with low line losses, which reduces the common problem of renewable energy sources located far from consumption centers. And further cost reduction and performance improvement of energy storage will be needed for large-scale deployment of solar and wind power and electric vehicles. So, while the required magnitude of renewable energy is vast, the transformation is achievable. For example, wind already accounts for 20 percent of Danish power production (box 4.13).

Renewable energy policies: financial incentives and regulations

Transparent, competitive, and stable pricing through long-term power purchase agreements has been most effective in attracting investors to renewable energy, and an enabling legal and regulatory framework can ensure fair and open grid access for independent power producers. Two major mandatory policies for renewable power generation are operating worldwide: feed-in laws that mandate a fixed price, and renewable portfolio standards that mandate a set target for the share of renewable energy (box 4.14).[89]

Feed-in laws require mandatory purchases of renewable energy at a fixed price. Feed-in laws such as those in Germany, Spain, Kenya, and South Africa produce the highest market penetration rates in a short period. They are considered most desirable by investors because of their price certainty and administrative simplicity and because they are conducive to creating local manufacturing industries. Three methods are commonly used to set prices for feed-in tariffs—avoided costs of conventional power generation, costs of renewable energy plus reasonable returns, and average retail prices (net metering allows consumers to sell excess electricity generated from their homes or businesses, usually through solar photovoltaics, to the grid at retail market prices). The main risk is in setting prices either too high or low, so feed-in tariffs need periodic adjustment.

Renewable portfolio standards require utilities in a given region to meet a minimum share of power in or level of installed capacity from renewable energy, as in many U.S. states, the United Kingdom, and Indian states. The target is met through utilities' own generation, power purchases from other producers, direct sales from third parties to the utility's customers, or purchases of tradable renewable energy certificates. But unless separate technology targets or tenders are in place, renewable portfolio standards lack price certainty and tend to favor established industry players and least-cost technologies.[90] They are also more complex to design and administer than feed-in laws.

BOX 4.13 *Denmark sustains economic growth while cutting emissions*

Between 1990 and 2006 Denmark's GDP grew at roughly 2.3 percent a year, more than Europe's average of 2 percent. Denmark also reduced carbon emissions by 5 percent.

Sound policies decoupled emissions from growth. Denmark, along with other Scandinavian countries, implemented the world's first carbon tax on fossil fuels in the early 1990s. At the same time Denmark also adopted a range of policies to promote the use of sustainable energy. Today around 25 percent of Denmark's electricity generation and 15 percent of its primary energy consumption come from renewable energy, mainly wind and biomass, with a goal to raise the use of renewable energy to at least 30 percent by 2025. Membership in the Nordic power pool, with more than 50 percent hydropower, provides the additional flexibility of exporting surplus wind power and importing Norwegian hydropower during periods of low wind resources. Vestas, the major Danish wind company, has 15,000 employees and accounts for a quarter of the global market for wind turbines. In 15 years Danish renewable technology exports have soared to $10.5 billion.

In addition to its low carbon-intensity of energy, Denmark has the lowest energy intensity in Europe, a result of stringent building and appliance codes and voluntary agreements on energy savings in industry. Combined heat- and power-based district heating networks provide 60 percent of the country's winter heating, with over 80 percent of it coming from heat previously wasted in electricity production.

Sources: WDR team based on WRI 2008; Denmark Energy Mix Fact Sheet, http://ec.europa.eu/energy/energy_policy/doc/factsheets/mix/mix_dk_en.pdf (accessed August 27, 2009).

BOX 4.14 *Feed-in laws, concessions, tax credits, and renewable portfolio standards in Germany, China, and the United States*

Developing countries account for 40 percent of global renewable energy capacity. By 2007, 60 countries, including 23 developing countries, had renewable energy policies.[a] The three countries with the largest installed capacity of new renewable energy are Germany, China, and the United States.

Germany's feed-in law

In the early 1990s Germany had virtually no renewable energy industry. Today it has become a global renewable energy leader, with a multibillion-dollar industry and 250,000 new jobs.[b] The government passed the Electricity Feed-in Law in 1990, requiring utilities to purchase the electricity generated from all renewable technologies at a fixed price. In 2000 the German Renewable Energy Act set feed-in tariffs for various renewable energy technologies for 20 years, based on their generation costs and generation capacity. To encourage cost reductions and innovation, prices will decline over time based on a predetermined formula. The law also distributed the incremental costs between wind power and conventional power among all utility customers in the country.[c]

China's renewable energy law and wind concession

China was one of the first developing countries to pass a renewable energy law, and it now has the world's largest renewable energy capacity, accounting for 8 percent of its energy and 17 percent of its electricity.[d] The law set feed-in tariffs for biomass power, but wind power tariffs are established through a concession process. The government introduced wind concessions in 2003 to ramp up wind power capacity and drive down costs. The winning bids for the initial rounds were below average costs and discouraged both wind developers and domestic manufacturers. Improvements in the concession scheme and provincial feed-in tariffs put China at no. 2 in newly installed wind capacity in 2008. The government's target of 30 gigawatts of wind by 2020 will likely be reached ahead of time. The domestic wind manufacturing industry has been boosted by the government's requirement of 70 percent local content and new technology transfer models to hire and acquire international design institutes.

U.S. federal production tax credits and state renewable portfolio standards

A federal tax credit for producing electricity from renewable energy has encouraged significant capacity increases, but the uncertainty of its extension from year to year has led to boom-and-bust cycles in U.S. wind development. And twenty-five states now have renewable portfolio standards. As a result, wind accounted for 35 percent of new generation capacity in 2007, and the United States now has the world's largest installed wind capacity.[e]

Sources:
a. REN 21 2008.
b. Federal Ministry for the Environment 2008.
c. Beck and Martinot 2004.
d. REN 21 2008.
e. Wiser and Bolinger 2008.

An alternative approach for achieving renewable energy targets is competitive tendering, where power producers bid on providing a fixed quantity of renewable power, with the lowest-price bidder winning the contract, as is done in China and Ireland. Tendering is effective at reducing costs, but a main risk has been that some bidders underbid and obligations have not always translated into projects on the ground.

Several financial incentives are available to encourage renewable energy investments: reducing up-front capital costs through subsidies; reducing capital and operating costs through investment or production tax credits; improving revenue streams with carbon credits; and providing financial support through concessional loans and guarantees. Output-based incentives are generally preferable to investment-based incentives for grid-connected renewable energy.[91] Investment incentives per kilowatt of installed capacity do not necessarily provide incentives to generate electricity or maintain the performance of plants. But output incentives per kilowatt-hour of power produced promote the desired outcome—generating electricity from renewable energy. Any incremental costs of renewable energy over fossil fuels can be passed on to consumers or financed through a system benefits charge, a carbon tax on fossil-fuel use, or a dedicated fund from government budgets or donors.

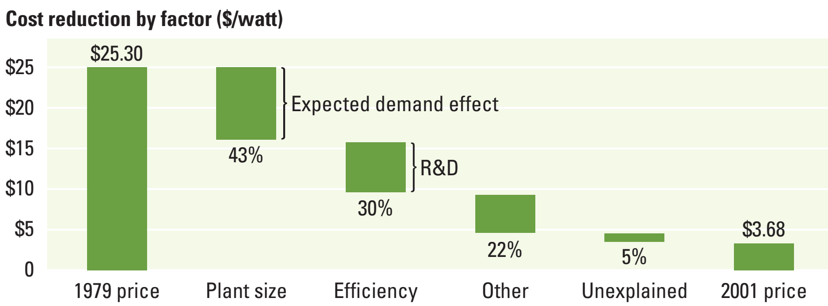
Nuclear power and natural gas

Nuclear power is a significant option for mitigating climate change, but it suffers from four problems: higher costs than coal-fired plants,[92] risks of nuclear weapon proliferation, uncertainties about waste management, and public concerns about reactor safety. Current international safeguards are inadequate to meet the security challenges of expanded nuclear deployment.[93] However, the next generation of nuclear reactor designs offer improved safety characteristics and better economics than the reactors currently in operation.

Nuclear power has large requirements for capital and highly trained personnel, with long lead times before it comes on line, thus reducing its potential for reducing carbon emissions in the short term. Planning, licensing, and constructing a single nuclear plant typically takes a decade or more. And because of the dearth of orders in recent decades, the world has limited capacity to manufacture many of the critical components of nuclear plants, and rebuilding that capacity will take at least a decade.[94]

Natural gas is the least carbon-intensive fossil fuel for power generation and for residential and industrial use. There is a large potential to reduce carbon emissions by substituting natural gas for coal in the short term. Some 2°C scenarios project that the share of natural gas in the primary energy mix will increase from 21 percent currently to 27–37 percent by 2050.[95] But the costs of natural gas-fired power depend on gas prices, which have been highly volatile in recent years. And, like oil, more than 70 percent of the world's gas reserves are in the Middle East and Eurasia. Security of gas supply is a concern for gas-importing countries. So energy diversification and supply security concerns could limit the share of natural gas in the global energy mix to less than indicated in some climate-energy models.[96]

Figure 4.12 Solar photovoltaic power is getting cheaper over time, thanks to R&D and higher expected demand from larger scale of production



Source: Adapted from Nemet 2006.

Note: Cost reduction is expressed in 2002 $. Bars show the portion of the reduction in the cost of solar photovoltaic power, from 1979 to 2001, accounted for by different factors such as plant size (which is determined by expected demand) and improved efficiency (which is driven by innovation from R&D). The "other" category includes reductions in the price of the key input silicon (12 percent) and a number of much smaller factors (including reduced quantities of silicon needed for a given energy output, and lower rates of discarded products due to manufacturing error).

Accelerating innovation and advanced technologies

Accelerating innovation and advanced technologies requires adequate carbon pricing; massive investment in research, development and demonstration; and unprecedented global cooperation (see chapter 7). Coupling technology push (by increasing research and development, for example) with demand pull (to increase economies of scale) is critical to substantially reduce the cost of advanced technologies (figure 4.12).

Utility-scale power generation technologies require policies and approaches different from those for small-scale technologies. An international Manhattan Project is likely to be needed to develop the former, such as power-plant-based carbon capture and storage, on a scale large enough to allow substantial cost reductions as the technology moves along the learning curve. Developers—utilities or independent power producers—usually have sufficient resources and capacity. But adequate carbon pricing and investment subsidies are required to overcome the high capital cost barrier. In contrast, decentralized, smaller-scale, clean energy technologies require that "a thousand flowers bloom" to address the needs of many small local players, with seed and venture capital and, in developing countries, business development advisory services.

To achieve the 2°C trajectory, a different technology path is required for developing countries. Energy and emissions growth are projected to come largely from developing countries, but developed countries attract much more investment in clean energy technology. Traditionally, new technologies are produced first in developed economies, followed by commercial roll-outs in developing countries, as has been the case with wind energy.[97] But for emissions to peak in 10 years to stay on the 2°C trajectory, both developed and developing countries would need to introduce large-scale demonstrations of advanced technologies now and in parallel. This pattern is fortunately emerging with the rapid advent of research and development in Brazil, China, India, and a few other technology leaders in the developing world. The lowest-cost manufacturers of solar cells, efficient lighting, and ethanol are all in developing countries.

One of the major barriers facing developing countries is the high incremental cost of developing and demonstrating advanced clean energy technologies. It is essential that developed countries substantially increase financial assistance and transfers of low-carbon technologies to the developing world through mechanisms such as a global technology fund. Developed countries will also need to take the lead in encouraging technological breakthroughs (see chapter 7). The Mediterranean Solar Plan is an example of cooperation between developed and developing countries on the large-scale demonstration and deployment of concentrated solar power (box 4.15).

BOX 4.15 *Concentrated solar power in the Middle East and North Africa*

The Mediterranean Solar Plan would create 20 gigawatts of concentrated solar power and other renewable energy capacity by 2020 to meet energy needs in the Middle Eastern and North African countries and export power to Europe. This ambitious plan could bring down the costs of concentrated solar power enough to make it competitive with fossil fuels. Concentrated solar power on less than 1 percent of Saharan desert area (see the map below) would meet Europe's entire power needs.

Financing this solar initiative will be a major challenge but offers an excellent opportunity for a partnership between developed and developing countries to scale up renewable energy for the benefit of both Europe and North Africa.

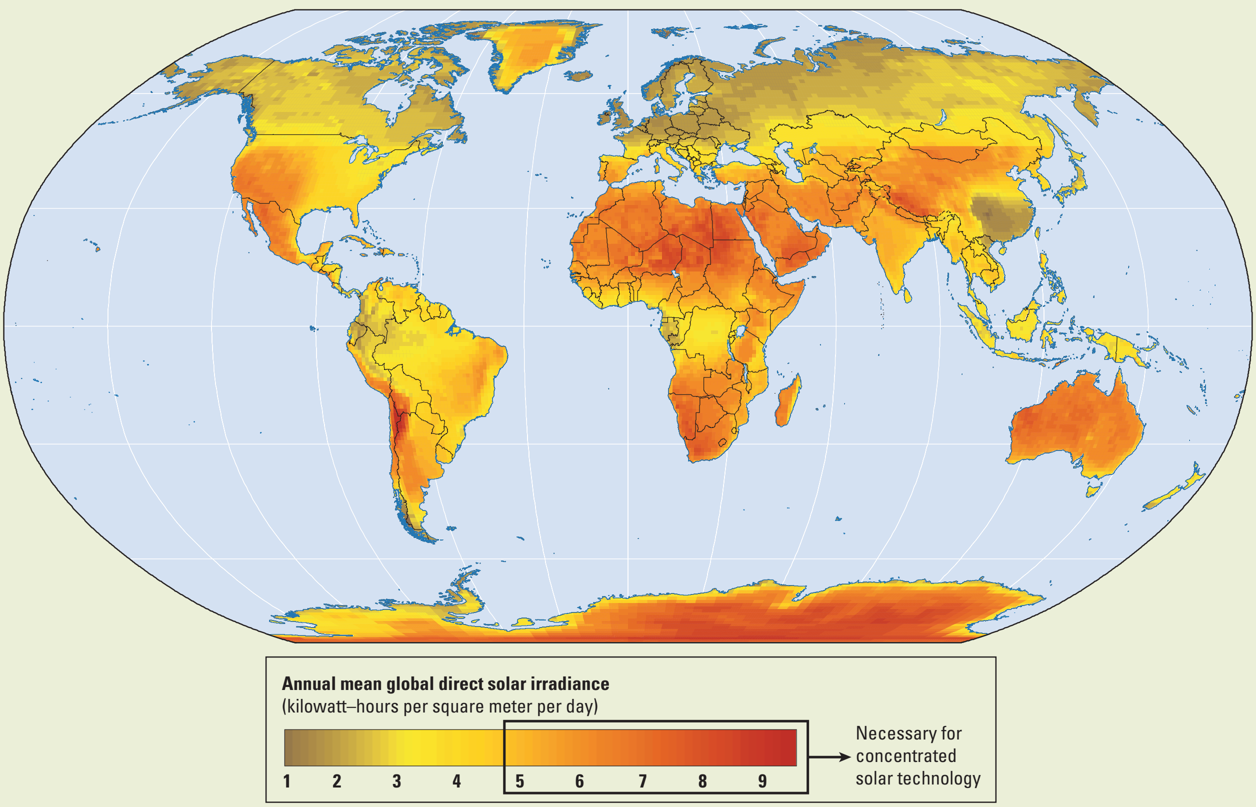
First, the demand for green electricity and the attractive renewable energy feed-in tariffs in Europe can significantly improve the financial viability of concentrated solar power.

Second, bilateral and multilateral funds—such as the Global Environment Facility, Clean Technology Fund, and carbon financing—would be required for investment subsidies, concessional financing, and revenue enhancement to cover the incremental costs of concentrated solar power, particularly for the portion meeting demand in domestic markets in the Middle East and North Africa.

Third, a successful program also calls for policy actions by the region's governments, creating an enabling environment for renewable energy and removing subsidies to fossil fuels.

Source: WDR team.

Global direct normal solar radiation (kilowatt-hours a square meter a day)



Source: United Nations Environmental Program, Solar and Wind Energy Resource Assessment, http://swera.unep.net/index.php?id=metainfo&rowid=277&metaid=386 (accessed July 21, 2009).

Policies have to be integrated

Policy instruments need to be coordinated and integrated to complement each other and reduce conflicts. A reduction of emissions in transport, for example, requires integration of a three-legged approach. In the order of difficulty, they are transforming vehicles (fuel efficient, plug-in hybrid, and electric cars), transforming fuels (ethanol from sugarcane, second generation biofuels, and hydrogen), and transforming mobility (urban planning and mass transit).[98] Biofuel policies need to coordinate energy and transport policies with agriculture, forestry, and land-use policies to manage the competing demands for water and land (see chapter 3). If energy crops take land away from agriculture in poor nations, the "medicine" of the requisite interventions might be worse than the "disease" in the sense that mitigation might increase vulnerability to climate impacts.[99] Large-scale deployment of plug-in hybrid and electric vehicles would substantially increase power demand, threatening the anticipated lower emissions from the technology unless the grid is supplied with an increased share of low-carbon energy sources. Policies to encourage renewable energy, if not designed properly, can discourage efficient heat production for combined heat and power.

Policies, strategies, and institutional arrangements also have to be aligned across sectors. Cross-sectoral initiatives are usually difficult to implement, because of fragmented institutional arrangements and weak incentives. Finding a champion is critical for moving the agenda forward; for example, local governments can be a good entry point for emission reductions in cities, particularly for buildings and modal shifts in transport. It is also important to align policies and strategies in national, provincial, and local governments (see chapter 8).

In conclusion low-carbon technology and policy solutions can put the world onto a 2°C trajectory, but a fundamental transformation is needed to decarbonize the energy sector. This requires immediate action, and global cooperation and commitment from developed and developing countries. There are win-win policies that governments can adopt now, including regulatory and institutional reforms, financial incentives, and financing mechanisms to scale up existing low-carbon technologies, particularly in the areas of energy efficiency and renewable energy.

Adequate carbon pricing and increased technology development are essential to accelerate development and deployment of advanced low-carbon technologies. Developed countries must take the lead in demonstrating their commitment to significant change at home, while also providing financing and low-carbon technologies to developing countries. Developing countries require paradigm shifts in new climate-smart development models. The technical and economic means exist for these transformative changes, but only strong political will and unprecedented global cooperation will make them happen.

Notes

1. IPCC 2007.

2. Authors' estimates; Socolow 2006. Estimates are based on 100 kilowatt-hours a month electricity consumption for a poor household with an average of seven people, equivalent to 170 kilowatt-hours a person-year. Electricity is pro-

"If nothing is done, we shall lose our beloved planet. It is our collective responsibility to find 'unselfish' solutions and fast before it's too late to reverse the damage caused every day."

—Maria Kassabian, Nigeria, age 10

vided at the current world average carbon intensity of 590 grams of CO_2 a kilowatt-hour for 1.6 billion people, equivalent to 160 million tons of CO_2. Socolow (2006) assumed providing 35 kilograms of clean cooking fuels (liquefied petroleum gas) for each of the 2.6 billion people would emit 275 million tons of CO_2. So a total of 435 million tons of CO_2 accounts for only 2 percent of current global emissions of 26,000 million tons of CO_2.

3. Black carbon, which is formed through the incomplete combustion of fossil fuels, contributes to global warming by absorbing heat in the atmosphere and, when deposited on snow and ice, by reducing their reflective power and accelerating melting. Unlike CO_2, black carbon remains in the atmosphere for only a few days or weeks, so reducing these emissions will have almost immediate mitigation impacts. In addition, black carbon is a major air pollutant and a leading cause of illness and premature death in many developing countries.

4. SEG 2007.

5. Wilbanks and others 2008.

6. McKinsey & Company 2009b.

7. Ebinger and others 2008.

8. The meaning and importance of energy security vary by country depending on its income, energy consumption, energy resources, and trading partners. For many countries dependence on imported oil and natural gas is a source of economic vulnerability and can lead to international tensions. The poorest countries (with per capita income of $300 or less) are particularly vulnerable to fuel price fluctuations, with an average 1.5 percent decrease in GDP associated with every $10 increase in the price of a barrel of oil (World Bank 2009a).

9. Increasing fuel prices by 20 percent increases the costs of generation by 16 percent for gas and 6 percent for coal, while leaving renewable energy practically untouched; see World Economic Forum 2009.

10. IEA 2008b.

11. WRI 2008; see also presentation of historical emissions in the overview.

12. IEA 2008c.

13. IPCC 2007.

14. United Nations 2007.

15. IEA 2008b.

16. Chamon, Mauro, and Okawa 2008.

17. Schipper 2007.

18. Lam and Tam 2002; 2000 U.S. Census, http://en.wikipedia.org/wiki/List_of_U.S._cities_with_most_households_without_a_car (accessed May 2009).

19. Kenworthy 2003.

20. District heating distributes heat for residential and commercial buildings that is supplied in a centralized location by efficient cogeneration plants or large-scale heating boilers.

21. Negative emissions can be achieved by sequestering carbon in terrestrial ecosystems (for example, by planting more forests). It could also be achieved by applying carbon capture and storage to biomass-produced energy.

22. A 450 ppm concentration of greenhouse gases translates into a 40–50 percent chance of temperatures not exceeding 2°C above preindustrial temperatures. Schaeffer and others 2008; Hare and Meinshausen 2006.

23. Tans 2009.

24. Rao and others 2008.

25. Biomass obtained from plants can be a carbon-neutral fuel, because carbon is taken up out of the atmosphere as the plants grow and is then released when the plants are burned as fuel. Biomass-based carbon capture and storage could result in large-scale "negative emissions" by capturing the carbon emitted from biomass combustion.

26. Weyant and others 2009; Knopf and others, forthcoming; Rao and others 2008; Calvin and others, forthcoming.

27. German Advisory Council on Global Change 2008; Wise and others 2009.

28. These five models (MESSAGE, MiniCAM, REMIND, IMAGE, and IEA ETP) are the global leading energy-climate models from Europe and the United States, with a balance of top-down and bottom-up approaches and different mitigation pathways. MESSAGE, developed by the International Institute for Applied Systems Analysis (IIASA), adopts the MESSAGE modeling system, which comprises energy systems engineering optimization model MESSAGE and the top-down macroeconomic equilibrium model MACRO, in addition to forest management model DIMA and agricultural modeling framework AEZ-BLS. This analysis considers the B2 scenarios, because they are intermediary between A2 (a high population growth case) and B1 (a plausible "best case" to achieve low emissions in the absence of vigorous climate policies), characterized by "dynamics as usual" rates of change (Riahi, Grübler, and Nakićenović 2007; Rao and others 2008). MiniCAM, developed at the Pacific Northwest National Laboratory, combines a technologically detailed global energy–economy–agricultural-land-use model with a suite of coupled gas-cycle, climate and ice-melt models (Edmonds and others 2008). REMIND, developed by Potsdam Institute for Climate Impact Research, is an optimal growth model that combines a top-down macroeconomic model with a bottom-up energy model, aiming at welfare maximization (Leimbach and others, forthcoming). IMAGE model, developed

by the Netherlands Environmental Assessment Agency, is an integrated assessment model including the TIMER 2 energy model coupled with the climate policy model FAIR-SiMCaP (Bouwman, Kram, and Goldewijk 2006). The fifth model is the IEA Energy Technology Perspective, a linear programming optimization model based on the MARKAL energy model (IEA 2008b).

29. Mitigation costs include additional capital investment costs, operation and maintenance costs, and fuel costs, compared to the baseline. Rao and others 2008; Knopf and others, forthcoming; Calvin and others, forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

30. Riahi, Grübler, and Nakićenović 2007; IIASA 2009; Knopf and others, forthcoming; IEA 2008c.

31. IEA 2008b; McKinsey & Company 2009a.

32. Knopf and others, forthcoming; Calvin and others, forthcoming; IEA 2008c.

33. Rao and others 2008; IEA 2008b; Mignone and others 2008. This is true in the absence of effective and acceptable geoengineering technology (see chapter 7 for a discussion).

34. IEA 2008b; IEA 2008c; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; Calvin and others, forthcoming.

35. Raupach and others 2007.

36. Shalizi and Lecocq 2009.

37. Philibert 2007.

38. McKinsey & Company 2009b.

39. World Bank 2001.

40. IEA 2008b; Calvin and others, forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

41. IEA 2008b; Calvin and others, forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009. The size of emission reductions required is critically dependent on the baseline scenarios, which vary greatly among different models.

42. IEA 2008b; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; IAC 2007. It should be noted that land-use changes and methane reductions are also critical measures in nonenergy sectors (see chapter 3) to achieve a 450 ppm CO_2e trajectory, particularly to buy some time in the short term for new technology development.

43. Knopf and others, forthcoming; Rao and others 2008.

44. Rao and others 2008; Calvin and others, forthcoming; Knopf and others, forthcoming.

45. Barrett 2003; Burtraw and others 2005.

46. A molecule of methane, the major component of natural gas, has 21 times more global warming potential than a molecule of CO_2.

47. SEG 2007.

48. IEA 2008b; McKinsey & Company 2009b.

49. de la Torre and others 2008.

50. McKinsey & Company 2009a.

51. The Mexico Low Carbon Study identified nearly half of the total potential for emissions reduction to be from interventions with positive net benefits (Johnson and others 2008).

52. Bosseboeuf and others 2007.

53. IEA 2008b; Worldwatch Institute 2009.

54. UNEP 2003.

55. IPCC 2007.

56. Brown, Southworth, and Stovall 2005; Burton and others 2008. A comprehensive review of empirical experience based on 146 green buildings in 10 countries concluded that green buildings cost on average about 2 percent more to build than conventional buildings and could reduce energy use by a median of 33 percent (Kats 2008).

57. Shalizi and Lecocq 2009.

58. Brown, Southworth, and Stovall 2005.

59. IEA 2008b.

60. Johnson and others 2008.

61. Brown, Southworth, and Stovall 2005; ETAAC 2008.

62. Johnson and others 2008.

63. Sorrell 2008.

64. IEA 2008c.

65. Stern 2007. A small share of the subsidies supports clean energy technologies, such as the $10 billion a year for renewables.

66. World Bank 2008a.

67. Sterner 2007.

68. UNEP 2008.

69. Ezzati and others 2004.

70. Wang and Smith 1999.

71. A carbon tax of $50 a ton of CO_2 translates to a tax on coal-fired power of 4.5 cents a kilowatt-hour, or a tax on petroleum of 45 cents a gallon (12 cents a liter).

72. Philibert 2007.

73. WBCSD 2008.

74. World Energy Council 2008.

75. Goldstein 2007.

76. Meyers, McMahon, and McNeil 2005.

77. Goldstein 2007.

78. An energy-efficient mortgage allows borrowers to qualify for a larger mortgage by including energy savings gleaned from home energy-efficiency measures.

79. ESMAP 2008.

80. World Bank 2008d.

81. Taylor and others 2008.

82. World Bank 2008b.

83. Each lamp costs about $1 under these bulk procurement programs, instead of $3–$5, plus another dollar of transaction costs for distribution, awareness and promotion, monitoring and verification, and testing.

84. ESMAP 2009.

85. Armel 2008.

86. IEA 2008b; Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

87. The costs of wind, geothermal, and hydro power vary greatly depending on resources and sites.

88. IEA 2008a.

89. ESMAP 2006.

90. For example, renewable portfolio standards tend to favor wind energy but discourage solar energy.

91. World Bank 2006.

92. MIT 2003; Keystone Center 2007.

93. MIT 2003.

94. Worldwatch Institute 2008; IEA 2008b.

95. Calvin and others, forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

96. Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

97. Gibbins and Chalmers 2008.

98. Sperling and Gordon 2008.

99. Weyant and others 2009.

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