# Pathways to a Low-Carbon Economy

## Version 2 of the Global Greenhouse Gas Abatement Cost Curve

McKinsey&Company

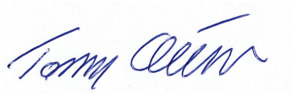
# Preface

Leaders in many nations are discussing ambitious targets for reducing emissions of greenhouse gases (GHGs). Some regions have already set reduction targets. The EU, for example, has set a target that 2020 emission levels should be 20% lower than those of 1990, and has stated its intention of aiming for a 30% reduction if other countries with high emissions also commit to comparable emission cuts. At the same time, an intense debate is underway regarding the technical and economic feasibility of different target levels, which emission reduction opportunities should be pursued, and the costs of different options for meeting the targets.

To provide a quantitative basis for such discussions, McKinsey & Company, supported by ten leading companies and organizations across the world, has developed a global greenhouse gas abatement data base. The abatement data base is comprised of an in-depth evaluation of the potential, and the costs, of more than 200 greenhouse gas abatement opportunities across 10 sectors and 21 world regions, and in a 2030 time perspective. This study builds on the earlier version of the global GHG abatement data base, conducted by McKinsey together with the Swedish utility Vattenfall, and published in January 2007. The current report incorporates updated assessments of the development of low-carbon technologies, updated macro-economic assessments, a significantly more detailed understanding of abatement potential in different regions and industries, an assessment of investment and financing needs in addition to cost estimates, and the incorporation of implementation scenarios for a more dynamic understanding of how abatement reductions could unfold. The financial crisis at the time of writing has not been taken into account in our analysis, based on the assumption that it will not have a major effect on a 2030 time horizon. This version of the report also reflects a deeper understanding by McKinsey into greenhouse gas abatement economics, gained through conducting 10 national greenhouse gas abatement studies during the last two years.

This study intentionally avoids any assessment of policies and regulatory choices. Instead, its purpose is to provide an objective and uniform set of data that can serve as a starting point for corporate leaders, academics, and policy makers when discussing how best to achieve emission reductions.

We would like to gratefully thank our sponsor organizations for supporting us with their expertise as well as financially: the Carbon Trust, ClimateWorks, Enel, Entergy, Holcim, Honeywell, Shell, Vattenfall, Volvo, and the World Wide Fund for Nature. We would also like to thank the members of our Academic Review Panel for their invaluable advice on the methodology and content of this study. Individual members of the panel might not necessarily endorse all aspects of the report: Dr. Fatih Birol (IEA, France), Prof. Mikiko Kainuma (NIES, Japan), Dr. Jiang Kejun (ERI, China), Dr. Ritu Mathur (TERI, India), Dr. Bert Metz (IPCC, Netherlands), Prof. Stephen Pacala (Princeton University, USA), Prof. Jayant Sathaye (LBNL, USA), and Prof. Lord Nicholas Stern (LSE, UK). Furthermore we thank the International Energy Agency for giving us access to their greenhouse gas emissions baseline. Finally we would like to thank our many colleagues within McKinsey who have helped us with advice and support.



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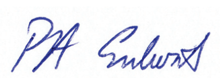

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Principal

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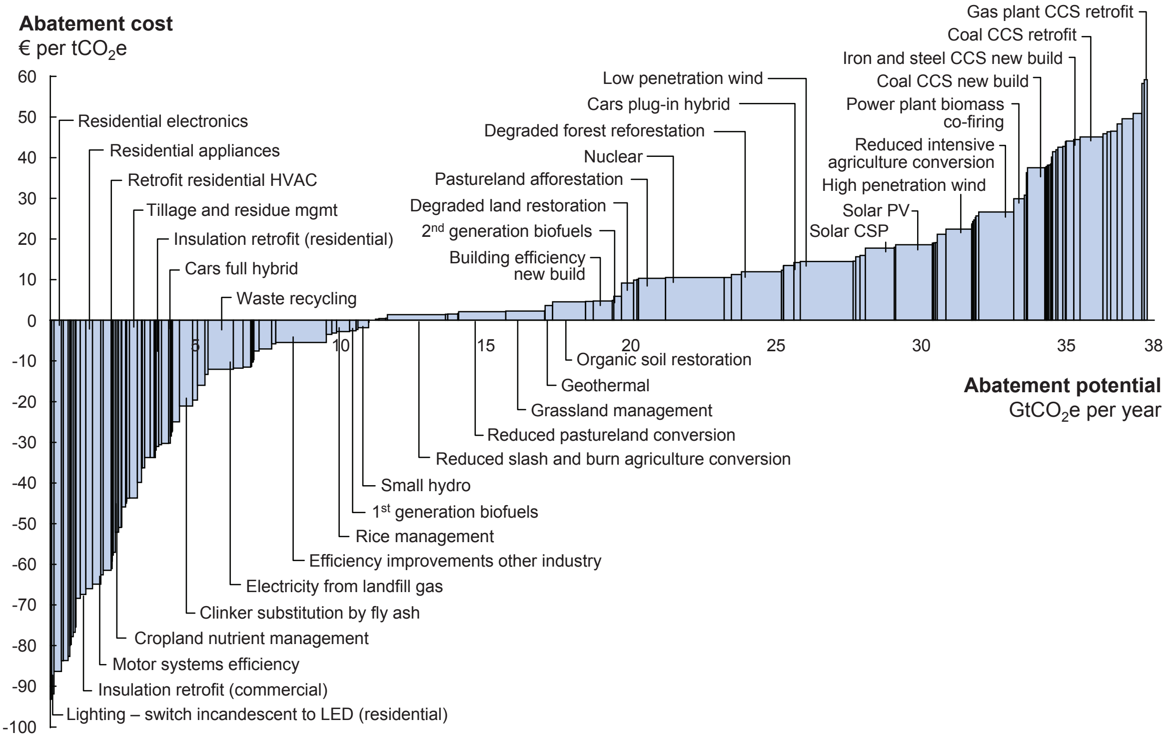
# Summary of findings

Leaders in many nations are discussing ambitious targets for reducing emissions of greenhouse gases (GHGs) in order to mitigate the worst impact of climate change on the environment, human societies, and our economies. Many scientists and policy makers, including those in the European Union, believe that holding the rise in global mean temperatures below 2 degrees Celsius compared with pre-industrial times is an important aim, as they see this as a threshold when the implications of global warming become very serious.

McKinsey & Company's greenhouse gas abatement cost curve provides a quantitative basis for discussions about what actions would be most effective in delivering emissions reductions, and what they might cost. It provides a global mapping of opportunities to reduce the emissions of GHGs across regions and sectors (Exhibit 1).

**Exhibit 1**

**Global GHG abatement cost curve beyond business-as-usual – 2030**




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

Our analysis finds that there is *potential* by 2030 to reduce GHG emissions by 35 percent compared with 1990 levels, or by 70 percent compared with the levels we would see in 2030 if the world collectively made little attempt to curb current and future emissions. This would be sufficient to have a good chance of holding global warming below the 2 degrees Celsius threshold, according to the Intergovernmental Panel on Climate Change (IPCC).[1]

Capturing enough of this potential to stay below the 2 degrees Celsius threshold will be highly challenging, however. Our research finds not only that all regions and sectors would have to capture close to the full potential for abatement that is available to them; even deep emission cuts in some sectors will not be sufficient. Action also needs to be timely. A 10-year delay in taking abatement action would make it virtually impossible to keep global warming below 2 degrees Celsius.

What would such an effort cost? We find that, if the most economically rational abatement opportunities are pursued to their full potential – clearly an optimistic assumption – the total worldwide cost could be €200 to 350 billion annually by 2030. This is less than 1 percent of forecasted global GDP in 2030, although the actual effect on GDP of such abatement efforts is a more complex matter that depends, among other things, on the financing of such abatement efforts. Turning to financing, the total upfront investment in abatement measures needed would be €530 billion in 2020 per year or €810 billion per year in 2030 – incremental to business-as-usual (BAU) investments. This corresponds to 5 to 6 percent of BAU investments in fixed assets in each respective year. As such, the investment required seems to be within the long-term capacity of global financial markets (as long as the current credit squeeze doesn't have significant consequences in this time horizon). Indeed, many of the opportunities would see future energy savings largely compensate for upfront investments.

1 The primary source of the climate science in this report is *Climate Change 2007, Fourth IPCC Assessment Report*, Intergovernmental Panel on Climate Change. We are also grateful to scientists Michel den Elzen, Detlef van Vuuren, and Malte Meinshausen for their contributions.

## Potential exists to contain global warming below 2 degrees Celsius

This study focuses on technical abatement opportunities costing less than €60 per tonne of $CO_2$ equivalent ($tCO_2e$), and these are the opportunities shown on our "GHG abatement cost curve" (see "How to read the Greenhouse Gas abatement cost curve").[2] We have defined technical abatement opportunities as not having a material effect on the lifestyle of consumers and our results are therefore consistent with continuing increases in global prosperity. We have made high-level estimates of the size of more expensive technical opportunities, as well as changes in the behavior of consumers, which could potentially offer further potential for abatement. However, because these prospects are subject to a high degree of uncertainty, we have made no attempt to quantify their cost.

### How to read the Greenhouse Gas abatement cost curve

McKinsey's global greenhouse gas abatement "cost curve" summarizes the technical opportunities (i.e., without a material impact on the lifestyle of consumers) to reduce emissions of greenhouse gases at a cost of up to €60 per $tCO_2e$ of avoided emissions. The cost curve shows the range of emission reduction actions that are possible with technologies that either are available today or offer a high degree of certainty about their potential in a 2030 time horizon.

The width of each bar represents the potential of that opportunity to reduce GHG emissions in a specific year compared to the business-as-usual development (BAU). The potential of each opportunity assumes aggressive global action starting in 2010 to capture that specific opportunity, and so does not represent a forecast of how each opportunity will develop. The height of each bar represents the average cost of avoiding 1 tonne of $CO_2e$ by 2030 through that opportunity. The cost is a weighted average across sub-opportunities, regions, and years. All costs are in 2005 real Euros. The graph is ordered left to right from the lowest-cost abatement opportunities to the highest-cost. The uncertainty can be significant for individual opportunities for both volume and cost estimates, in particular for the Forestry and Agriculture sectors, and for emerging technologies.

The priority in our research has been to look at the global emission reduction opportunities with one consistent methodology, rather than to deep dive in any individual emission reduction opportunity.

Therefore, the curve should be used for overall comparisons of the size and cost of different opportunities, the relative importance of different sectors and regions, and the overall size of the emission reduction opportunity, rather than for predictions of the development of individual technologies. It can also be used as a simulation tool, testing for different implementation scenarios, energy prices, interest rates and technological developments.

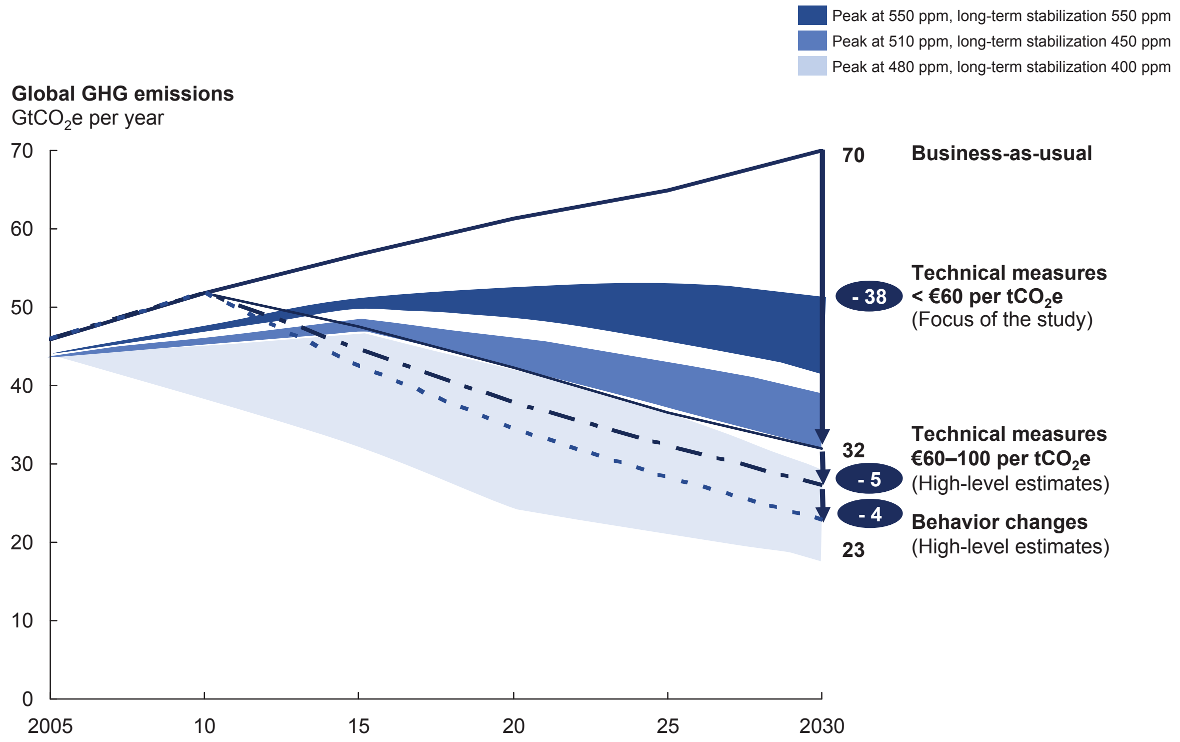
The reader should also bear in mind that the cost of abatement is calculated from a societal perspective (i.e., excluding taxes, subsidies, and with a capital cost similar to government bond rates). This methodology is useful because it allows for comparisons of opportunities and costs across countries, sectors and individual opportunities. However, it also means that the costs calculated are different from the costs a company or consumer would see, as these decision makers would include taxes, subsidies, and different interest rates in their calculations. Therefore, the curve cannot be used for determining switching economics between investments, nor for forecasting $CO_2$ prices. The cost of each opportunity also excludes transaction and program costs to implement the opportunity at a large scale, as these are highly dependent on how policy makers choose to implement each opportunity.

2 Using IPCC terminology, we studied the economic potential below €60 per $tCO_2e$ of technical emission reduction opportunities. We chose an economic cut-off to enable us to compare the size of opportunities within different sectors and regions in an objective way. We chose €60 per $tCO_2e$ as higher-cost measures tend to be early-stage technologies with development paths that are difficult to project.

The cost curve identifies a potential abatement of 38 $GtCO_2e$ (Exhibit 2) in 2030, relative to BAU emissions of 70 $GtCO_2e$. Our high-level estimates of additional potential from more expensive technical measures and changes in behavior, adds up to an additional 9 $GtCO_2e$. Theoretically, capturing the full abatement potential across sectors and regions starting in 2010, 2030 emissions would be between 35 and 40 percent lower than they were in 1990, the reference year for the Kyoto Protocol and many current discussions. Relative to the 2030 business-as-usual (BAU) emissions[3], emissions would decrease by 65 to 70 percent. These emission levels would be broadly consistent with an emissions pathway that would see the atmospheric concentration of GHGs peaking at 480 parts per million (ppm) and then start decreasing. According to the IPCC's analysis, such a pathway would result in a likely average increase of the global mean temperature of just below 2 degrees Celsius.

**Exhibit 2**

## Emissions relative to different GHG concentration pathways




Note: As a reference, 1990 total emissions were 36 Gt $CO_2e$
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; IPCC; den Elzen; Meinshausen; OECD; US EPA; van Vuuren

## Capturing the full abatement potential is a major challenge

It is one thing to have the *potential* to make deep cuts in GHG emissions; it is another for policy makers to agree on and implement effective emission reduction policies, and for companies, consumers and the public sector to take action to make this reduction a reality. Capturing all the opportunities would entail change on a huge scale. In Transport, for instance, the assumption in our study is that 42 million hybrid vehicles (including plug-ins) could be sold by 2030 – that's a full 40 percent of all new car sales.

3 To build a comprehensive BAU projection, we combined the projections of the International Energy Agency's (IEA) World Energy Outlook 2007 for $CO_2$ emissions from energy usage, Houghton's projections for $CO_2$ emissions from land use and land-use change, and the US Environmental Protection Agency's (EPA) projections for non-$CO_2$ GHGs. See chapter 2 for details.

In Forestry, the assumption is that we could until 2030 avoid the deforestation of 170 million hectares, equivalent to twice the land area of Venezuela, and plant new forests on 330 million hectares of currently marginal land – the equivalent of foresting much of India. In Power, the share of low-carbon generation technologies such as renewables, nuclear and carbon capture and storage have could rise to about 70 percent of global electricity production from 30 percent in 2005. After careful analysis, we believe such change would be feasible if there was concerted global action to go after each opportunity – this is the potential we aim to portray in our curve – but implementing all of the opportunities on our curve to their full extent clearly represents a massive change.

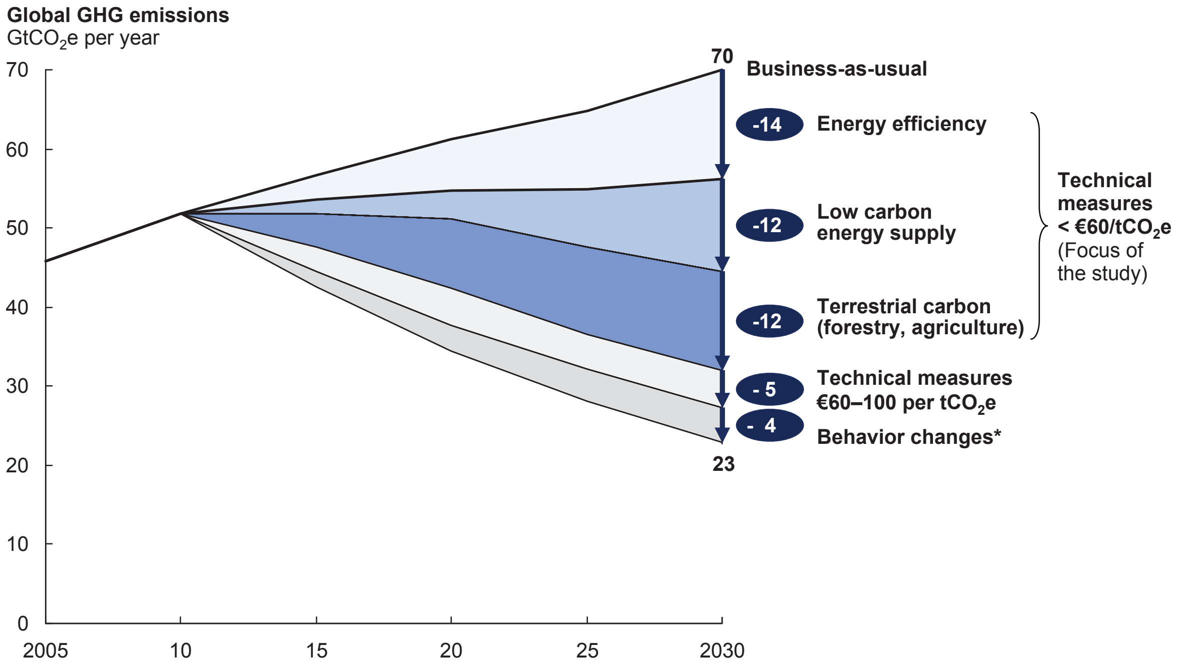
Another way to illustrate the challenge is to look at carbon productivity – the amount of GDP produced per unit of $CO_2$ emitted. In the period from 2005 to 2030, emissions would need to decrease by 35 to 50 percent to attain a pathway likely to achieve the 2 degrees Celsius threshold. As the world economy is set to more than double during the same time period, this implies almost quadrupling the global carbon productivity. This corresponds to increasing the annual global carbon productivity gains from 1.2 percent in the BAU, to 5 to 7 percent.

## Four major categories of abatement opportunities

The abatement opportunities in the period between now and 2030 fall into four categories: energy efficiency, low-carbon energy supply, terrestrial carbon (forestry and agriculture), and behavioral change. The first three, technical abatement opportunities which are the focus of our study, add up to a total abatement opportunity of 38 $GtCO_2e$ per year in 2030 relative to annual BAU emissions of 70 $GtCO_2e$ (Exhibit 3)[4]:

**Exhibit 3**

### Major categories of abatement opportunities




* The estimate of behavioral change abatement potential was made after implementation of all technical levers; the potential would be higher if modeled before implementation of the technical levers.
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; US EPA

4 Key abatement data for 2020 can be found in the appendix.

- **Energy efficiency (opportunity of 14 Gt$CO_2$e per year in 2030).** There are a large number of opportunities to improve the energy efficiency of vehicles, buildings, and industrial equipment, thereby reducing energy consumption. More fuel-efficient car engines, better insulation of buildings, and efficiency controls on manufacturing equipment are just a few of the possibilities. If all energy efficiency opportunities identified in our research were captured, annual growth in global electricity demand between 2005 and 2030 would be reduced from 2.7 percent per year in the BAU case to about 1.5 percent.
- **Low-carbon energy supply (opportunity of 12 Gt$CO_2$e per year in 2030).** There are many opportunities to shift energy supply from fossil fuels to low-carbon alternatives. Key examples include electricity production from wind, nuclear, or hydro power, as well as equipping fossil fuel plants with carbon capture and storage (CCS), and replacing conventional transportation fuel with biofuels. If these low-carbon alternatives were to be fully implemented, we estimate that they have the potential to provide about 70 percent of global electricity supply by 2030 compared with just 30 percent in 2005; and that biofuels could provide as much as 25 percent of global transportation fuel by 2030. This would constitute a major shift in global energy supply. Several of these low-carbon energy technologies are too expensive today to deploy on a large scale without financial incentives, emphasizing the need to provide sufficient support to make them travel down the learning curve allowing them to contribute to their full potential.[5]
- **Terrestrial carbon – forestry and agriculture (opportunity of 12 Gt$CO_2$e per year in 2030).** Forests and soils act as natural sinks for carbon. Halting ongoing tropical deforestation, reforesting marginal areas of land, and sequestering more $CO_2$ in soils through changing agricultural practices would increase carbon sequestration. This would lead to negative net emissions of $CO_2$e into the atmosphere from these sectors in the period we have studied (implying that more carbon is stored than is released from these sinks), a major abatement opportunity versus the BAU in which deforestation continues. However, capturing these opportunities would be highly challenging. More than 90 percent of them are located in the developing world, they are tightly linked to the overall social and economic situation in the concerned regions, and addressing the opportunities at this scale has not before been attempted. Our estimate of the feasibility and cost of this opportunity is therefore subject to significant uncertainty. We also note that terrestrial carbon opportunities are temporary in nature because the sinks would saturate between 2030 and 2050, so that, at the end of this period, there would be few additional areas of marginal land left available for re-forestation.

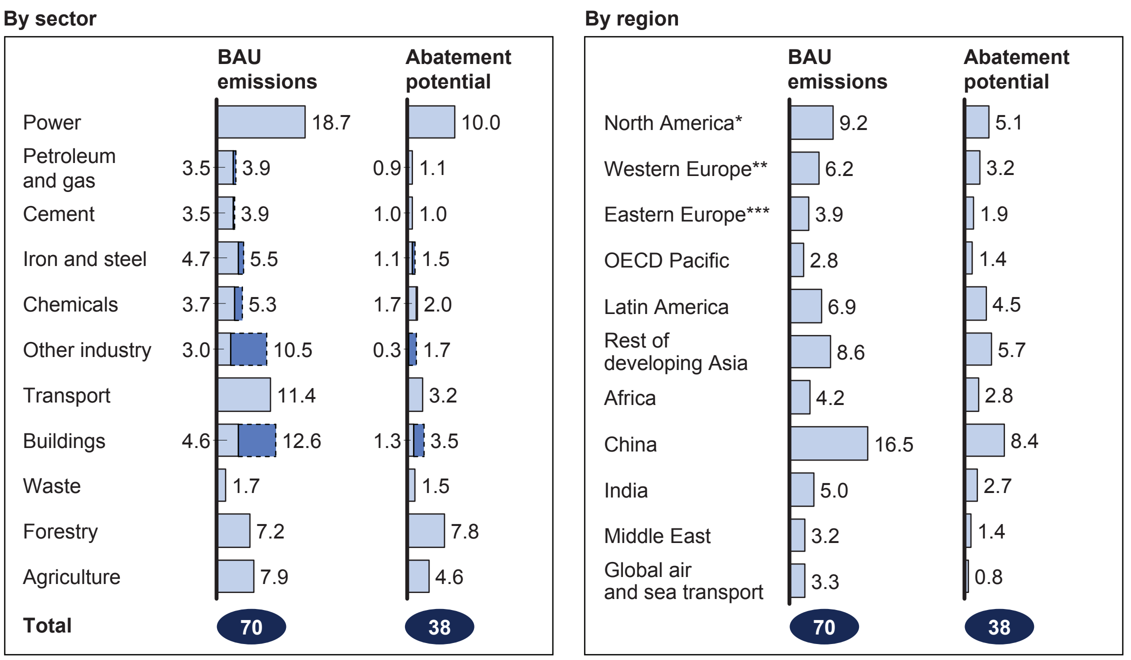
Abatement opportunities in these three categories are spread across many sectors of the economy. Approximately 29 percent of the total is in energy supply sectors (electricity, petroleum and gas), 16 percent in the industrial sector, 22 percent in sectors with significant consumer influence (transportation, buildings, waste), and the remaining 33 percent in land-use related sectors (forestry and agriculture). Some 30 percent of the total opportunity is located in the developed world and 70 percent in the developing world (Exhibit 4). A key driver for the high share of abatement potential in developing regions is the fact that a very large share of the opportunity in forestry and agriculture resides there. It should be noted that the relative share of abatement potential in different regions does not imply anything about who should pay for emissions reduction.

5 We have only included technologies in our curve that we see as technologically proven, that could credibly have costs lower than €60 per t$CO_2$e abated in 2030, and that we can envisage having a major abatement impact by 2030. There are also many technologies that did not pass our criteria to be included in the curve since they are too early in their development stage, but that could also have a major impact in the period after 2030.

**Exhibit 4**

## Emissions and abatement potential by sector and region

$GtCO_2e$ per year; 2030




* United States and Canada
** Includes EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, Switzerland
*** Russia and non-OECD Eastern Europe
Note: To obtain the total BAU emissions, only direct emissions are to be summed up. To obtain total abatement potential, indirect emission savings need to be included in the sum.
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; UNFCCC; US EPA

We estimate that another 3.0–6.0 $GtCO_2e$ per year of technical abatement opportunities in these three categories are available at a cost of between €60 and €100 per $tCO_2e$. This range of higher cost abatement has not been the focus of our research, and the level of uncertainty in our estimates is much higher than for the lower cost opportunities. Examples of these more expensive abatement opportunities include retiring relatively young fossil fuel based power plants and replacing them with low-carbon options and in heavy industry, additional energy efficiency measures are possible if the cost threshold is increased.

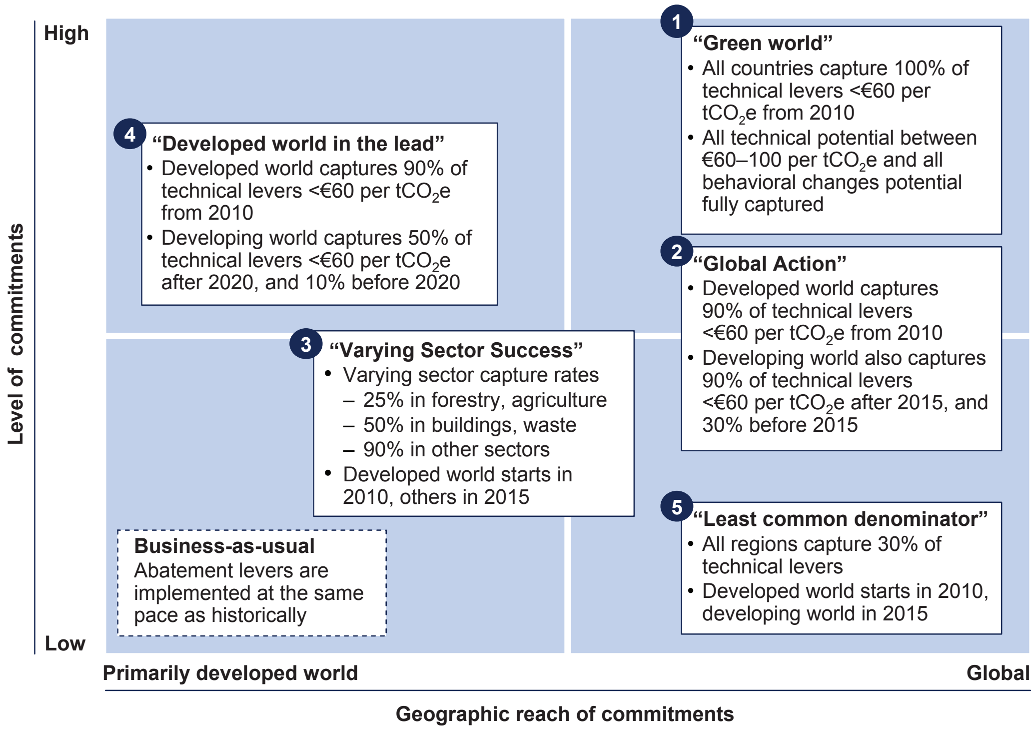
The fourth category of abatement opportunity is behavioral change. In an optimistic case – and there is a high degree of uncertainty in these estimates – this could yield between another 3.5–5.0 $GtCO_2e$ per year of abatement in 2030. Key opportunities include reducing business and private travel, shifting road transport to rail, accepting higher domestic temperature variations (reducing heating/cooling), reducing appliance use, and reducing meat consumption. Changing behavior is difficult and the abatement realized would depend heavily on whether, and to what extent, policy makers establish effective incentives.

### All regions and sectors need to maximize their capture of the emissions potential

The fragmentation of the opportunity across sectors and regions demonstrates the importance of global cross-sector action to cut emissions, regardless of who pays for such efforts. The 38 $GtCO_2e$ of abatement on our 2030 cost curve is a maximum potential estimate that assumes the effective implementation of all abatement opportunities, starting promptly in 2010. In reality, there will likely be delays in policy action, and varying ambition levels and success rates of businesses and consumers when going after the opportunities. Our analysis of five different implementation scenarios finds that, if there are significant shortfalls in any major sector or region, measures in other sectors or regions – even at a higher cost – would only partly be able to compensate (see Chapter 6 of this report for detail on the five scenarios and Exhibit 5 for a summary).

**Exhibit 5**

**Integrated implementation scenarios 2010–2030**




Source: Global GHG Abatement Cost Curve v2.0

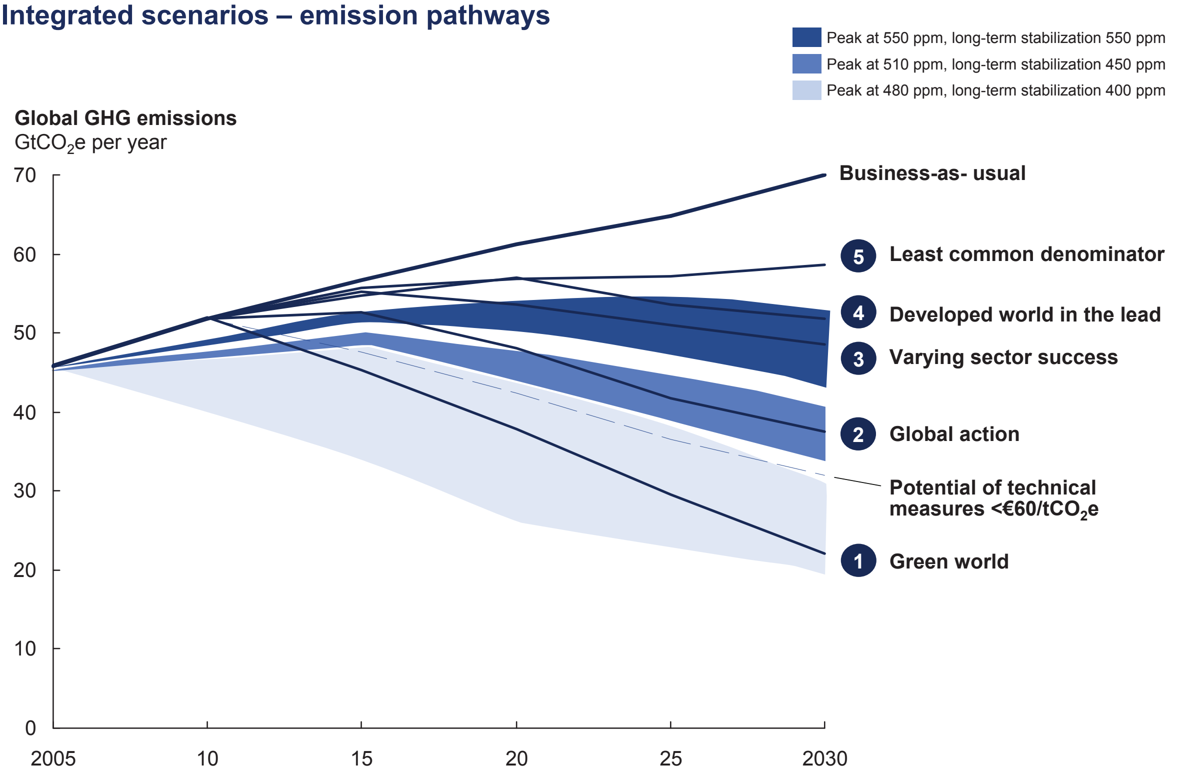
We find that only our "Green World" and "Global Action" scenarios, both of which assume an aggressive global commitment to abate GHGs across regions and sectors, would achieve pathways with a significant chance of containing global warming below 2 degrees Celsius (Exhibit 6). The three other scenarios would put the world on track to achieve a 550 ppm pathway or higher that would offer only a 15–30 percent likelihood of limiting global warming to below 2 degrees Celsius, according to the external estimates we have used.

## Delaying action for 10 years would mean missing 2 degrees Celsius aim

If policy makers aim to stabilize global warming below 2 degrees Celsius, time is of the essence. Our model shows that if global abatement action were to start in 2020 instead of 2010, it would be challenging to achieve even a 550 ppm stabilization path, even if more expensive technical measures and behavioral changes were also implemented (Exhibit 7).

**Exhibit 6**

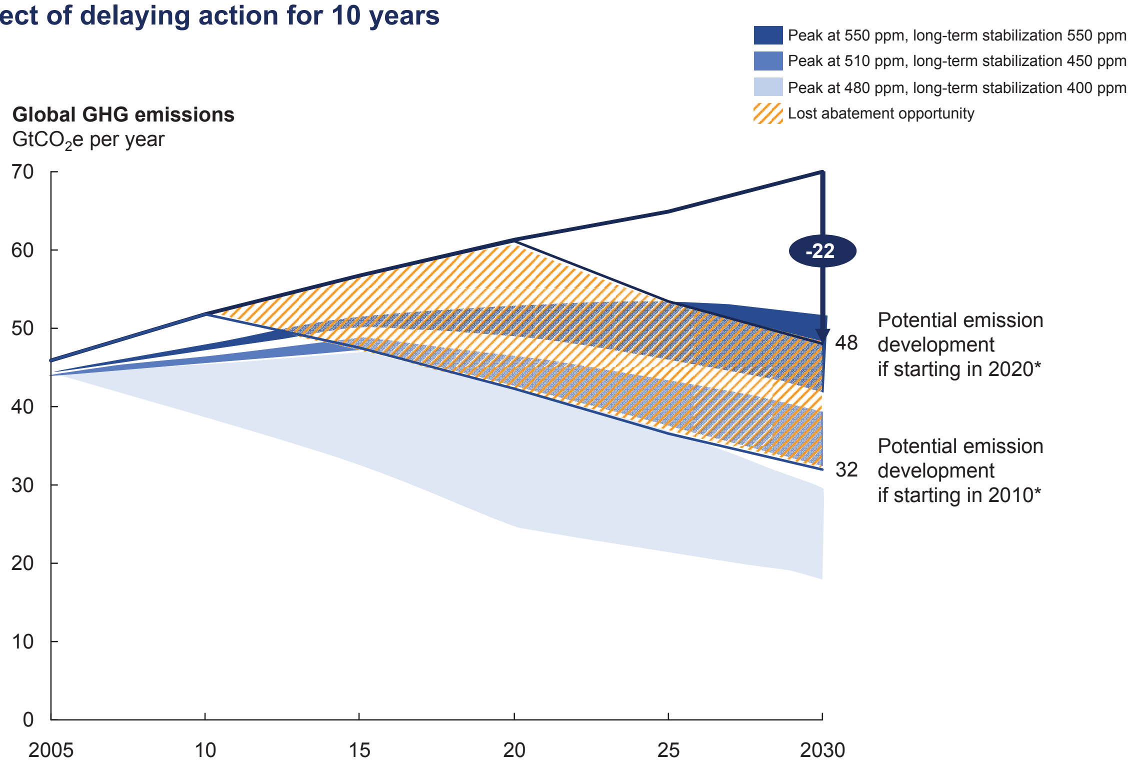
## Integrated scenarios – emission pathways




Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; IPCC; den Elzen; Meinshausen; OECD; US EPA; van Vuuren

**Exhibit 7**

## Effect of delaying action for 10 years




* Technical levers <€60/$tCO_2e$

Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; OECD; EPA; den Elzen; van Vuuren, Meinshausen

First, and most obvious, delay would mean that emissions would continue to grow according to the BAU development instead of declining. Second, building high-carbon infrastructure in sectors such as Buildings, Power, Industry, and Transport would lock in higher energy use for decades to come. In our model, the effective lifetime of carbon-intense infrastructure across sectors is, on average, 14 years. The result is that by delaying action for one year, an estimated 1.8 $GtCO_2e$ of abatement would be lost in that specific year[6]. Consequently, the world would be committed to cumulative emissions over the next 14 years of 25 $GtCO_2e$. In terms of atmospheric concentration, the continued BAU emissions growth coupled with the lock-in effect would lead to a 5 ppm higher expected peak $CO_2e$ concentration.[7]

## Future energy savings could largely pay for upfront investments

If the world were to successfully implement every measure on the cost curve, in strict order from low-cost to higher-cost in sequence – in other words be more economically rational than reality would normally suggest – the theoretical average cost of the abatement opportunities would be €4 per $tCO_2e$ in 2030, and the total cost for realizing the whole curve would be some €150 billion. Transaction and program costs, that are not part of our curve[8], are often estimated at an average of between €1 and 5 per $tCO_2e$ abated, making a total of approximately €40 to 200 billion for the 38 $GtCO_2e$ of abatement opportunities on our cost curve. This would make the total annual global cost approximately €200 to 350 billion by 2030. This estimate should be treated with significant caution for two reasons: One, the assumption that opportunities would effectively be addressed from left to right in our curve is a highly optimistic one. Two, there would in reality be significant dynamic effects in the economy from a program of this magnitude – effects that could work to either increase or decrease the cost depending on how they were implemented and that have not been taken into account in our analysis.

A large share of the abatement opportunities involves investing additional resources upfront to make existing or new infrastructure more carbon efficient – including all energy efficiency measures and much of the renewable energy measures – and then recouping part or all of that investment through lower energy or fuel spending in the future. There is about 11 $GtCO_2e$ per year of abatement potential in 2030 in which energy savings actually outweigh the upfront investment. In short, these measures would have a net economic benefit over their lifetime, even without any additional $CO_2$ incentive. If there are such substantial opportunities with net economic benefits over time, why haven't consumers and entrepreneurs already captured this potential? The reason is that a range of market imperfections, such as agency issues, act as a barrier and disincentive to making the necessary investments. As an example, builders have little incentive to add insulation beyond technical norms to new homes when it is the home-owner, not the builder, who will enjoy lower energy bills during the next decades.

6 Calculated as the difference in emissions caused by infrastructure built in the year 2010 in the BAU versus if all low-carbon options according to our curve were pursued.

7 The effect of a 10-year delay is that 2030 emissions end up in middle of the stabilization path that peaks at 550 ppm, instead of at the high end of the path that peaks at 480 ppm. Rounding the difference to 50 ppm (to account for the fact that emissions end up in the middle of the 550 ppm scenario and the high end of the 480 ppm scenario) makes the effect 5 ppm per year.

8 The reason for this is that such costs reflect political choices about which policies and programs to implement and vary from case to case. It is therefore not possible to incorporate these costs in the abatement curve in an objective way and maintain the ability to compare abatement potentials across regions and sectors.

## Globally, financing looks manageable, but individual sectors will face big challenges

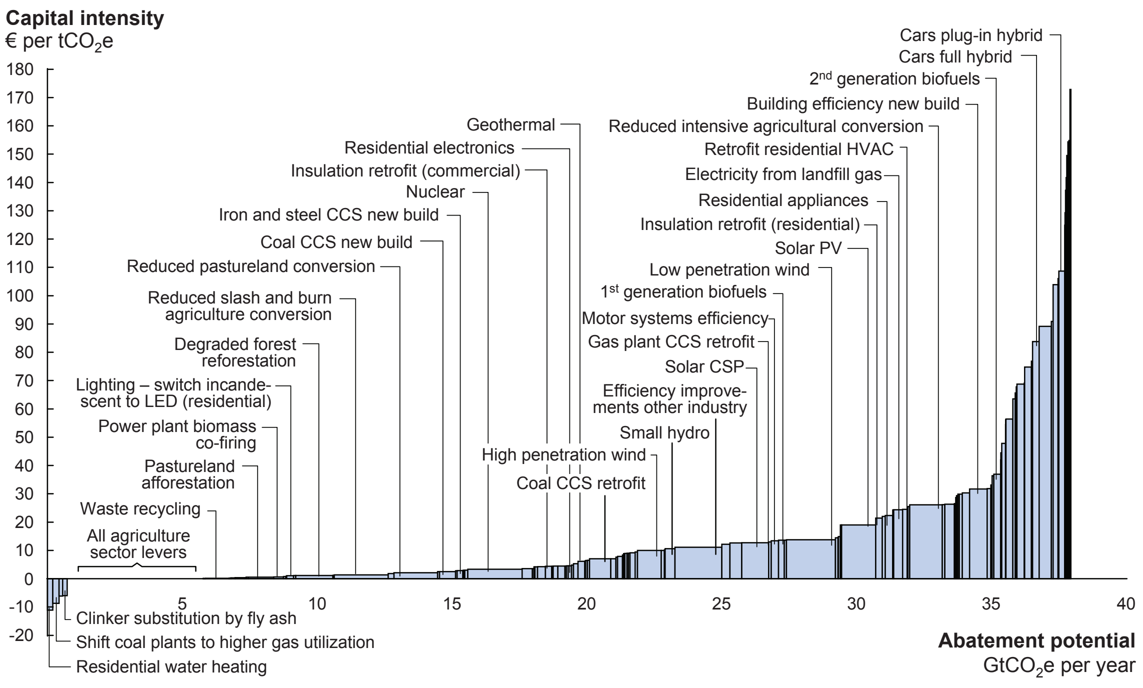
The total investment to achieve all the measures on our cost curve amounts to €530 billion per year in 2020 and €810 billion per year in 2030, on top of BAU investments that would happen anyway. This corresponds to 5 to 6 percent of the BAU investments in fixed assets in each respective year. While financing is a major test in the current credit squeeze, it seems unlikely to us that, at the global level, financing these additional investments would be a bottleneck to action on reducing emissions in a 2030 time horizon.

A more detailed view at the investments required highlights possible financing challenges at a sector and regional level. Indeed, over 60 percent of the investments required in addition to the BAU turn out to be needed in the Transport and Buildings sectors, and close to 60 percent of the total investments turn out to be needed in developing countries. Although the net additional cost of investing in fuel-efficient vehicles and energy-efficient houses is typically low, as much of the investment is regained through energy savings, finding effective ways to incentivize and finance the (sometimes considerable) additional upfront expenditure may not be easy.

When analyzing the capital intensity[9] of individual abatement opportunities, it becomes clear that the cheapest abatement opportunities are not always those with the lowest capital spend (Exhibit 8).

**Exhibit 8**

### Capital intensity by abatement measure




Source: Global GHG Abatement Cost Curve v2.0

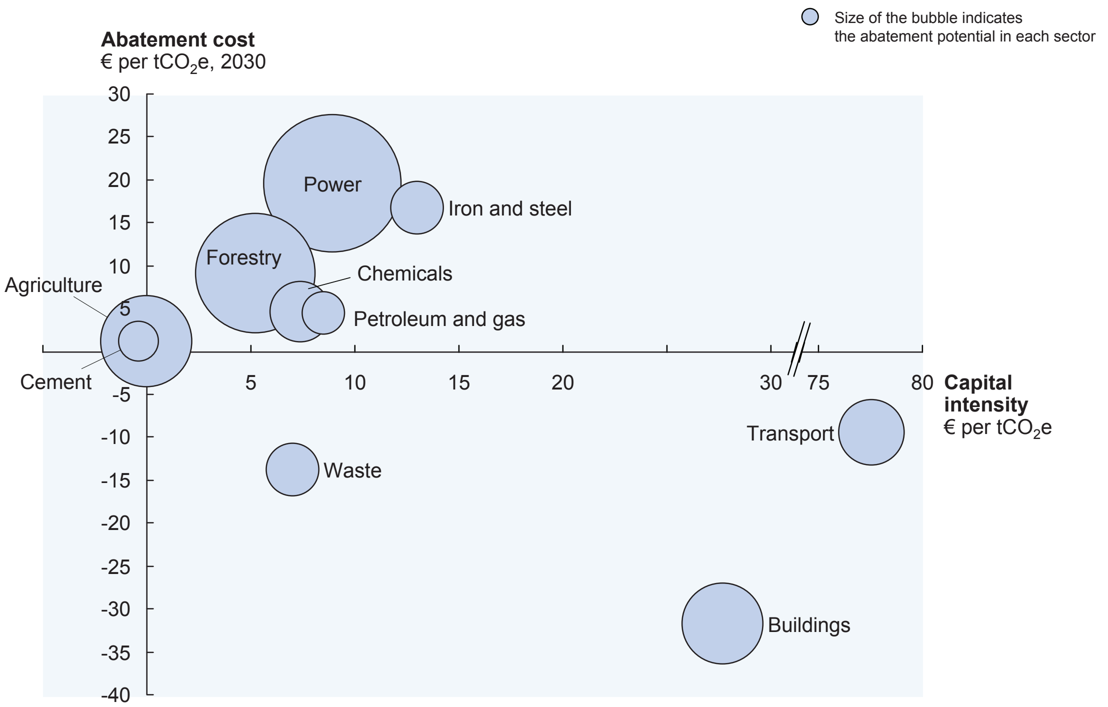
9 We define the capital intensity of an abatement measure as the additional upfront investment relative to the BAU technology, divided by the total amount of avoided emissions over the lifetime of the asset. For a more fuel efficient car, for instance, the capital intensity would be calculated as the additional upfront investment compared to the BAU technology, divided by the amount of $CO_2$ saved through lower fuel consumption during the lifetime of the car. The main difference with abatement cost is that the capital intensity calculation does not take financial savings through lower energy consumption into account.

For instance, many energy-efficiency opportunities that appear on the left-hand side of the cost curve end up much further to the right in the capital intensity curve. This demonstrates the different priorities that could emerge in a capital-constrained environment. Investors might choose to fund the opportunities with the lowest capital intensity rather than the ones with lowest cost over time. This would make the cost of abatement substantially higher over time.

Comparing the abatement cost and investments shows that the implementation challenges will be very different across sectors (Exhibit 9). In Transport and Buildings, upfront financing might be challenging but the cost is actually low once investments have been made. In several of the industrial sectors, average abatement costs are relatively high whereas upfront investments are lower. Making the abatement happen in these sectors is likely more a question about compensating companies for the high costs, than it is about financing the investments. Finally, in Forestry and Agriculture, both costs and investments are relatively low. Here, the implementation challenges are practical rather than economical, namely, designing effective policy and an effective way of measuring and monitoring the abatement.

**Exhibit 9**

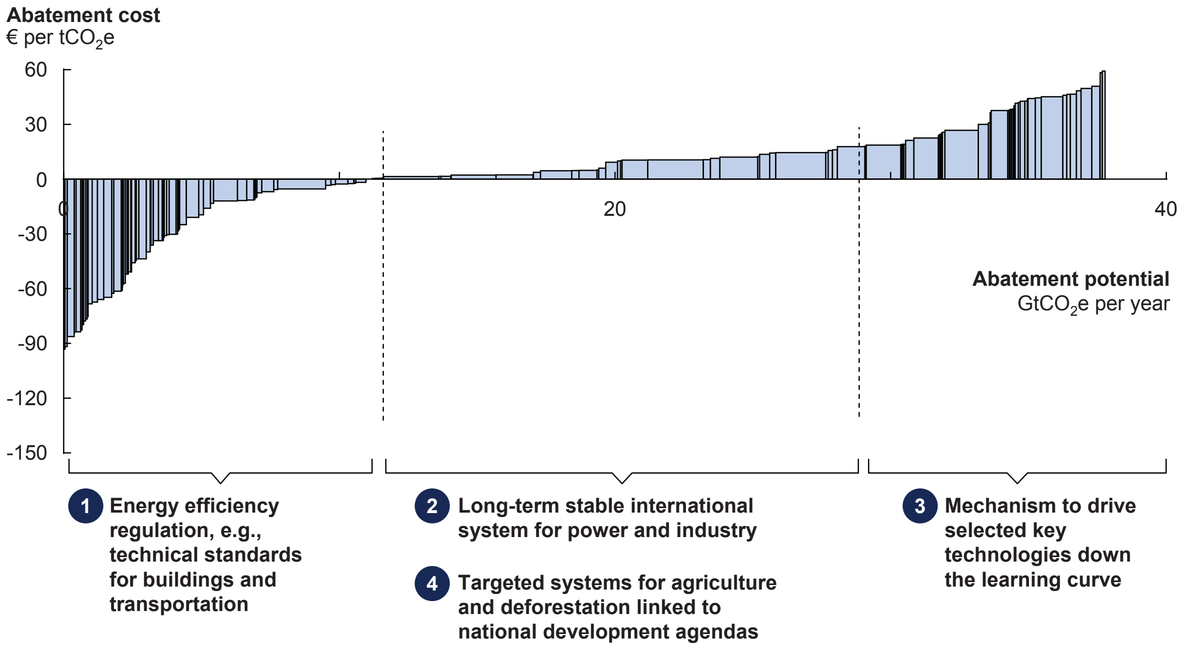
## Capital intensity and abatement cost




Source: Global GHG Abatement Cost Curve v2.0

Exhibit 10

## Key areas of regulation




Source: Global GHG Abatement Cost Curve v2.0

### Four areas of regulation will be key to achieving low-cost emission reduction

Achieving the deep emission cuts deemed necessary by the IPCC to stabilize global temperatures presents a huge policy challenge. Although we do not take a view on what policies decision makers should implement, we highlight four policy areas that we believe will be important to reduce emissions at the lowest possible cost (Exhibit 10):

1. Implementing regulation to overcome the market imperfections that prevent the energy efficiency opportunities with net economic benefits from materializing, e.g., through technical norms and standards;
2. Establishing stable long-term incentives to encourage power producers and industrial companies to develop and deploy greenhouse gas efficient technologies, e.g., in the form of a $CO_2$ price or a $CO_2$ tax;
3. Providing sufficient incentives and support to improve the cost efficiency of promising emerging technologies; and
4. Ensuring that the potential in forestry and agriculture is effectively addressed, primarily in developing economies, linking any system to capture abatement closely to their overall development agenda.

* * *

This study does not take a view on current climate science, but rather focuses on providing an objective, globally consistent data set on opportunities to reduce GHG emissions and their likely cost and investments. We hope that this analysis will serve as a useful starting point for discussions among companies, policy makers, and academics on how best to manage the transition to a low-carbon economy.

# 1. Objectives and approach

During 2006, McKinsey and the Swedish utility Vattenfall collaborated to develop a global greenhouse gas (GHG) abatement cost curve. The project aspired to map the global opportunities to reduce emissions of GHGs and to quantify the impact on emissions, and the cost of each opportunity. The objective was to provide the first globally consistent dataset as a starting point for global discussions about how to reduce GHG emissions, showing the relative importance of different sectors, regions, and abatement measures, and providing a factual basis on the costs of reducing emissions.

As we continue to analyze opportunities for the abatement of emissions, we are gradually improving the resolution and depth of the map we are creating. We might characterize the first version of the Global Cost Curve as a 16th century map of the world of the economics of global climate change mitigation. Version 2 has, perhaps, brought us into the 18th century. This report significantly updates and complements the original GHG abatement cost curve in several respects:

1. This report significantly enhances the resolution of our sector, regional, and temporal analysis. We now model GHG abatement opportunities for 10 sectors, 21 regions, and five timeframes (five-year intervals from 2005 to 2030).[10]
2. We have updated the data set to reflect the best current view on the business-as-usual emissions development, the future trajectory of energy prices, and on the development of low-carbon technologies.
3. We have modeled investment levels and cash-flow implications in addition to abatement costs.
4. We have studied several different implementation scenarios and sensitivities to enable a more dynamic view on emission reduction pathways than provided in our first report on the cost curve.
5. We have also incorporated the insights McKinsey has gained over the last two years from conducting national GHG abatement projects for several of the world's largest economies.[11]

10 The 10 sectors are Power, Petroleum and Gas, Cement, Iron and Steel, Chemicals, Transport, Buildings, Forestry, Agriculture, and Waste. The 21 regions we cover are G8+5 countries plus "rest of regions": Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Russia, South Africa, United Kingdom, United States, Middle East, Rest of Latin America, Rest of EU27, Rest of OECD Europe, Rest of Eastern Europe, Rest of Africa, Rest of developing Asia, and Rest of OECD Pacific.

11 McKinsey has published a number of national GHG abatement studies, often in cooperation with or on behalf of other organizations, including analyses of the cost curve in Australia, Czech Republic, Germany, Sweden, Switzerland, the United Kingdom, and the United States. All of these are available at www.mckinsey.com/clientservice/ccsi. Several other national studies are ongoing.

Consistent with McKinsey's original cost-curve analysis, we apply a strictly economic lens to the issue of emission reductions. While we realize that the choice of which GHG emission reduction measures to implement involves many noneconomic considerations, we believe that economics is a useful starting point for discussions about how to reduce emissions. We have also opted to analyze the broadest possible scope of GHG emissions to cover all major sectors, world regions, and types of GHGs. We believe that such a comprehensive view is necessary to arrive at effective factual comparisons between options in different sectors and regions, and to compare global opportunities to reduce emissions with the emission pathways that the Intergovernmental Panel on Climate Change (IPCC) estimates to be necessary.

By opting for such a broad analytical scope, we necessarily limit the depth to which we can explore individual emission reduction opportunities. There are plenty of global investigations that go much deeper into individual opportunities such as wind power, biofuels, and passive houses. We hope the value of our work is that instead it takes a global, cross-sector view using a single consistent methodology, therefore allowing for effective comparisons of the size and cost of different opportunities.

As in our first report, we explicitly avoid drawing conclusions about which policy regimes would be most effective or fair; nor do we assess current climate science, drawing instead on the analysis of the IPCC and IPCC authors.

We should note that the cost curve embodies a large set of assumptions to estimate available opportunities to abate GHGs. While we believe that our figures are reasonable estimates given the information available, readers should be aware that by necessity when estimating 20 years into the future, many of these figures contain a considerable uncertainty.

We have developed our assessment of the opportunities available to reduce emissions in each sector in cooperation with our ten sponsor organizations, an extensive network of experts from industry and academia, and McKinsey's own expert network.

# 2. The challenge of rising GHG emissions

## 2.1 Why do GHG emissions matter?

According to the Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report, "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations"[12]. The IPCC continues laying out what average global temperature increase it expects if global emissions continue to grow at their historic pace – between 2 and 6 degrees Celsius by the end of this century relative to pre-industrial levels. To stop this development, the IPCC report argues, deep emission cuts are required. The IPCC does not argue for any specific target in temperature or emissions, but the European Union has stated that it would like to see containing global warming below an average temperature increase of 2 degrees Celsius as a global ambition. At this level, the IPCC already expects to see large environmental, humanitarian, and economic consequences.

To assess the potential impact of different abatement measures on GHG concentration levels and therefore the global temperature, we compare post-abatement emissions with three exemplary allowable emissions pathways (i.e., ranges of emissions that would still allow the world to contain global warming). McKinsey has not made any assessment or analysis of these pathways, a task that is beyond our expertise. The estimates are those of external scientific sources, including the IPCC's Fourth Assessment Report that showed pathways for $CO_2$ and recent multigas studies from IPCC authors[13] (Exhibit 2.1.1).

The pathway values represent the absolute annual emissions over time that would need to be achieved in order to limit the increase in global mean temperature to a certain level[14]. There are two major uncertainties in the climate system which require the use of ranges: First, there is uncertainty about which path of annual emissions leads to a particular level of GHG concentration. Second, there are uncertainties about the translation of a concentration level pathway into a temperature trajectory. Three pathways have been used:

- **A pathway that peaks at 480 ppm.** This pathway is estimated to have a 70–85 percent probability of containing global warming below the 2 degrees Celsius threshold, and an expected

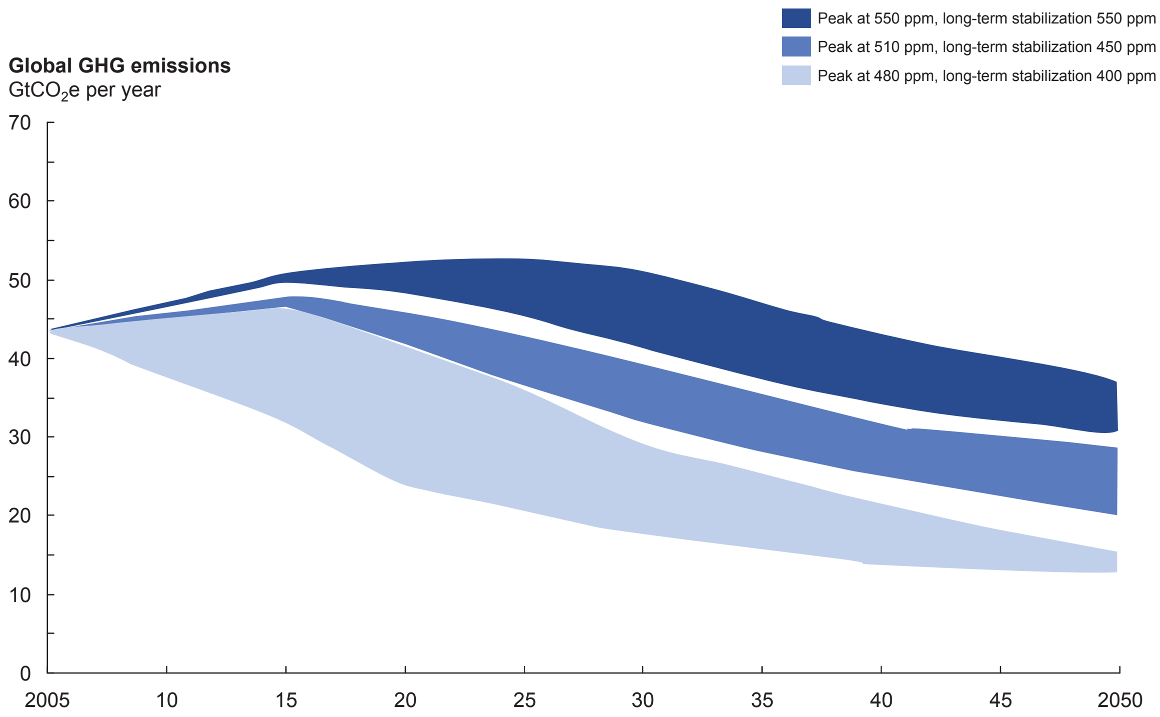
12 *Climate Change 2007, Fourth IPCC Assessment Report*, Intergovernmental Panel on Climate Change

13 We are grateful to scientists Michel den Elzen, Detlef van Vuuren, and Malte Meinshausen for their contributions to this report.

14 The stated temperature increase represents a global average with substantial variances around the globe – higher increases expected at the poles, lower increases towards the equator.

Exhibit 2.1.1

## Allowable emission pathways over time




Source: den Elzen; Meinshausen; van Vuuren; Global GHG Abatement Cost Curve v2.0

temperature increase is 1.8 degrees Celsius. In this pathway emissions would peak before 2015 and concentration levels would peak at 480 ppm $CO_2e$ between 2060 and 2070. The peaking of the concentration levels assumes that $CO_2$ emissions are reduced below the level of natural absorption. In this pathway, 2030 emissions would be 18–29 $GtCO_2e$ compared with 36 $GtCO_2e$ in 1990, a reduction of 20 to 50 percent during this period. In the very long term – likely around the year 2200 but there is significant uncertainty in this estimate – this pathway would achieve a stabilization level of 400 ppm if emissions constantly stay below natural absorption rates.

- **A pathway that peaks at 510 ppm.** This pathway would see emissions peak in or before 2015 and GHG concentration levels peak at 510 ppm $CO_2e$ before 2100. This pathway is estimated to have a 40 to 60 percent probability of containing global warming below the 2 degrees Celsius threshold, and the expected temperature increase is 2.0 degrees Celsius. In this pathway, 2030 emissions are of 32–39 $GtCO_2e$. Compared to 1990 levels this represents a change in emissions between plus 8 and minus 10 percent. Again, the long-term stabilization level of 450 ppm would not be anticipated until 2200.
- **A pathway that peaks and stabilizes at 550 ppm.** In this pathway, a concentration level of 550 ppm would be reached in 2060 without overshooting (i.e., peak and long-term stabilization levels would be equal), given today's starting position. In this pathway, emissions in 2030 would reach 41-51 $GtCO_2e$ compared with 1990 emissions of 36 $GtCO_2e$. This pathway is expected to lead to a temperature increase of 3.0 degrees Celsius.

The first two scenarios are so-called *overshoot* scenarios, where GHG concentration levels peak at one level, and then in the very long term stabilize at a lower level. For this lower stabilization level to materialize, they assume global $CO_2$ emissions will for a long time – more than a century – remain below the natural $CO_2$ absorption rate of the climate system. Our analysis only focuses on the time period to 2030. As a result, the peak concentration levels are more relevant to compare to.

## 2.2 Business-as-usual emissions trajectory

Global GHG emissions have increased steadily since the Industrial Revolution. Since 1990, the reference year used in the Kyoto protocol, emissions have grown at a pace of approximately 1.6 percent a year, from 36 gigatonnes of carbon dioxide equivalents ($GtCO_2e$) in 1990 to 46 $GtCO_2e$ in 2005. Most current research forecasts that, in the absence of major global policy action, global emissions will continue to grow at a similar pace as they have historically, driven by world population growth and rising wealth.

Drawing from external sources widely acknowledged to have some of the most comprehensive projections of GHG emissions, we see the business-as-usual (BAU) global anthropogenic GHG emissions increasing by around 55 percent in the period from 2005 to 2030, going from 46 to 70 $GtCO_2e$[15] per year, a growth of 1.7% per year.[16] Key assumptions in the BAU case are annual GDP growth of 2.1 percent in the developed world and 5.5 percent in the developing world; global population growth of 0.9 percent per annum, comprising 0.2 percent in developed countries and 1.1 percent in the developing world, and a $60 per barrel oil price. These assumptions are taken from the International Energy Agency's (IEA) *World Energy Outlook* for 2007. The emissions baseline is subject to substantial uncertainty, mainly due to uncertainty in GDP growth and population growth assumptions as well as how carbon-intense development paths countries choose. The abatement potential and consequently the achieveable emissions development over time, is strongly linked to the baseline.

This growth in emissions already includes a certain amount of decarbonization, best described in terms of carbon productivity – the amount of GDP produced per unit of $CO_2e$ emitted. In the period from 2005 to 2030, as the world economy is set to double, the annual carbon productivity improves by 1.2 percent annually in business-as-usual, broadly in line with historic improvements in this measure.[17] This decarbonization derives mainly from energy efficiency improvements happening under the usual course of the world economy. Details on decarbonization assumptions can be found for each of the sectors in the appendix.

Emissions fall into four broad groups of sectors that each contributed approximately one-quarter of total emissions in 2005: Power; Industry (with Petroleum and Gas, Iron and Steel, Cement, and Chemicals as large contributors); consumer-related sectors (i.e., Transport, Buildings, Waste), and land-use related sectors (i.e., Forestry and Agriculture) (Exhibit 2.2.1). Under BAU, the relative share of emissions from the first three groups will increase by a projected 2 to 3 percentage points each, while the relative share of land-use related emissions will fall from 30 percent in 2005 to an estimated 22 percent in 2030.

Our analysis also splits emissions by region (Exhibit 2.2.2). In 2005, the developed world contributed approximately 40 percent of total emissions, the developing world approximately 56 percent, with the remaining 4 percent coming from global air and sea transportation that in line with international agreements is not attributed to a specific region. Under BAU, the developed world will contribute 32 percent of the total by 2030, the developing world 63 percent, and global air and sea transport 5 percent.

In per capita terms, 2005 emissions were approximately 14 $tCO_2e$ per year in the developed world and 5 $tCO_2e$ per year in the developing world. By 2030, per capita emissions in the developed world are expected to remain more than twice as high as those in the developing world (16 and 7 $tCO_2e$ per year, respectively), despite the fact that expected annual growth in developed countries of 0.7 percent on average is only one third of the 2.2 percent growth rate in developing countries.

15 Our total BAU emissions in 2005 of 46 $GtCO_2e$ per year are slightly lower than the value from the IPCC AR4 of 49 $GtCO_2e$ per year. This gap is driven by different estimates of emissions from fossil fuel combustion (~1 Gt difference between the IPCC and the IEA); for non-$CO_2$ gases (~1 Gt difference between the IPCC and the US EPA); in LULUCF emissions (~1 Gt difference between the IPCC and Houghton/UNFCCC/Hooijer). The BAU emissions projection to 2030 is in line with IPCC's high-growth A1 Fossil Intensive (A1FI) scenario.

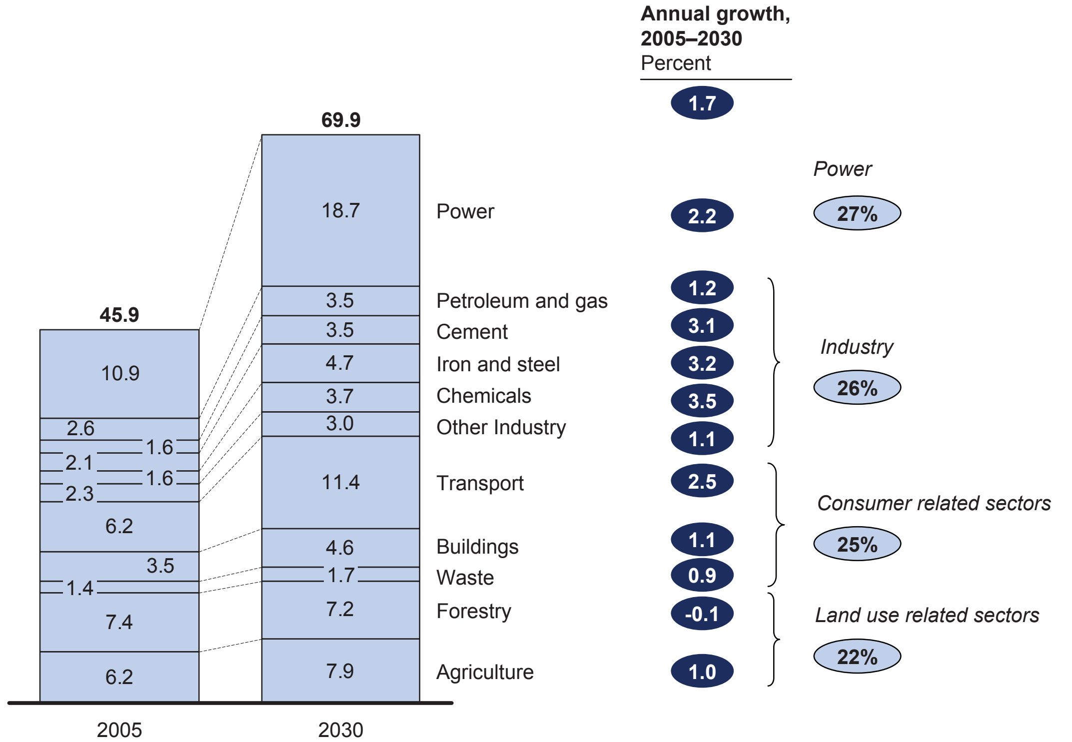
16 For our BAU analysis, we draw directly from a range of expert sources: the International Energy Agency (IEA) for $CO_2$ emissions from fossil-fuel combustion; Houghton 2003 revised, UNFCCC and IPCC for land-use, land-use change and forestry (LULUCF) emissions including peat, and the US Environmental Protection Agency (EPA) for emissions of non-$CO_2$ GHGs. For the Industry sectors, we constructed emission baselines leveraging IEA data wherever possible.

17 We measure carbon productivity as the ratio of global GDP to tonnes of global GHG emissions.

**Exhibit 2.2.1**

## Business-as-usual emissions split by sector in 2005 and 2030

$GtCO_2e$ per year

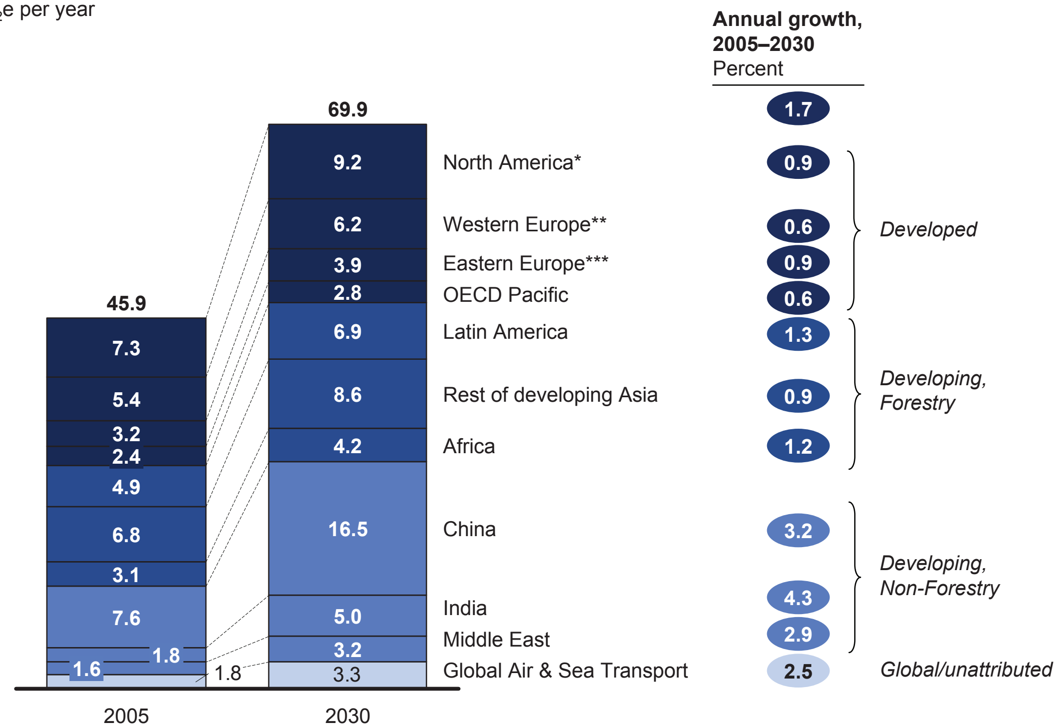



Source: Houghton; IEA; IPCC; UNFCCC; US EPA; Global GHG Abatement Cost Curve v2.0

**Exhibit 2.2.2**

## Business-as-usual emissions split by region in 2005 and 2030

$GtCO_2e$ per year




* US and Canada
** EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, and Switzerland
*** Non-OECD Eastern Europe and Russia.
Source: Houghton; IEA; IPCC; UNFCCC; US EPA; Global GHG Abatement Cost Curve v2.0

# 3. The GHG abatement potential

Our research finds that there is *potential* by 2030 to cut emissions by ~35 percent compared with 2005 levels and 70 percent compared with the levels that we would see in 2030 if the world failed to take action to curb emissions (a BAU development). If this full potential was captured, emissions would peak at 480 ppm and then start to decrease. As described in Chapter 2, this GHG concentration pathway is projected to very likely hold global warming below the 2 degrees Celsius threshold.

It is, however, one thing to have the *potential* to make deep cuts in GHG emissions; it is another for policy makers to agree on and implement effective emission reduction policies, and for companies, consumers and the public sector to take action to make this reduction a reality. The abatement potential we identify in the cost curve pushes the envelope in terms of what the world could achieve if each opportunity was pursued aggressively across regions (see section 6.1 of this report for a description of five implementation scenarios) and represents a huge challenge, capturing all the opportunities would entail change on a huge scale. In Transport, for instance, the assumption in our study is that 42 million hybrid vehicles (including plug-ins) could be sold by 2030 – that's a full 40 percent of all new car sales. In Forestry, the assumption is that we could until 2030 avoid the deforestation of 170 million hectares, equivalent to twice the land area of Venezuela, and plant new forests on 330 million hectares of currently marginal land – the equivalent of foresting much of India. In Power, the share of low-carbon generation technologies such as renewables, nuclear and carbon capture and storage could rise to about 70 percent of global electricity production from 30 percent in 2005. After careful analysis, we believe such change would be feasible if there was concerted global action to go after each opportunity – this is the potential we aim to portray in our curve – but clearly implementing all of the opportunities on our curve to their full extent represents a massive change.

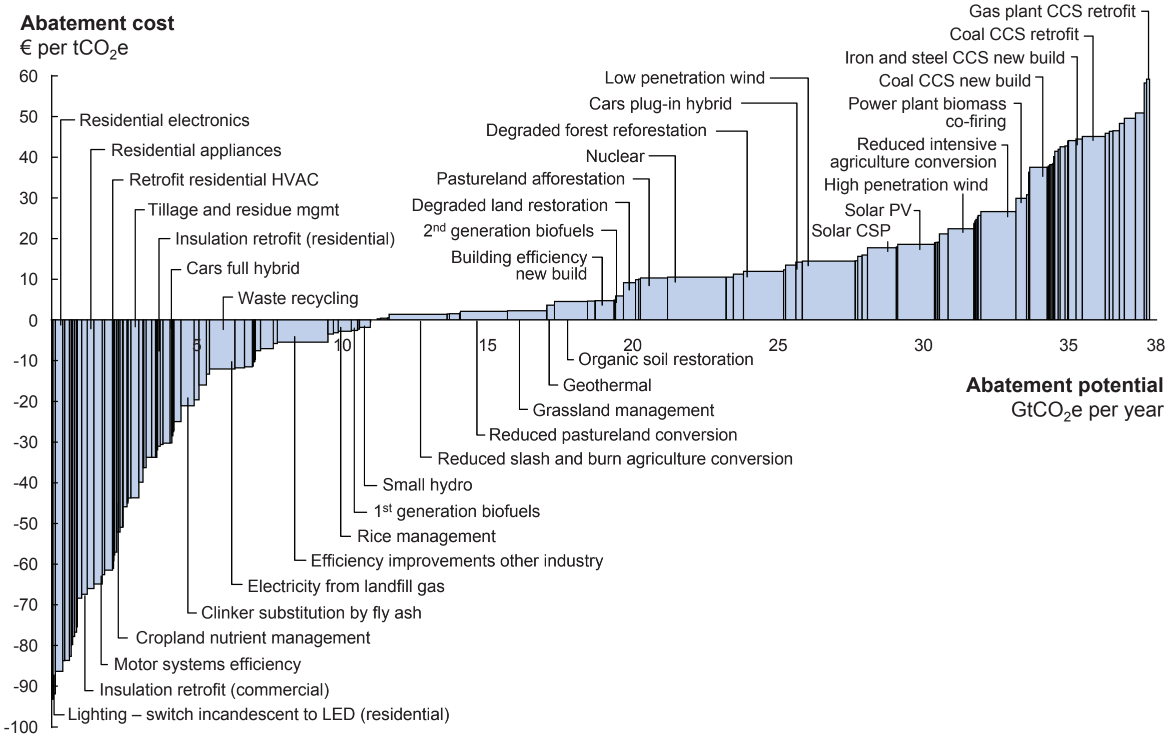
Another way to illustrate the challenge is to look at carbon productivity – the amount of GDP produced per unit of $CO_2$ emitted. In the period from 2005 to 2030, emissions would need to decrease by 35 to 50 percent to attain the 480 ppm peak pathway likely to achieve the 2 degrees Celsius threshold. As the world economy is set to more than double during the same time period, this implies almost quadrupling the global carbon productivity. This corresponds to increasing the annual global carbon productivity gains from 1.2 percent in the BAU, to 5 to 7 percent. In per capita terms – a third way to look at the challenge – reaching the emissions pathway that peaks at 480 ppm means reducing emissions from 7.1 $tCO_2e$ per capita in 2005 to 3.1 $tCO_2e$ per capita in 2030.

## Potential exists to contain global warming below 2 degrees Celsius – but not much more

Our research has identified that technical abatement measures costing less than €60 per $tCO_2e$ – the focus of most of our analysis – have the potential to deliver abatement of some 38 $GtCO_2e$ per year in 2030 (Exhibit 3.0.1). If the entire potential below this cost threshold was realized, 2030 emissions would be 55 percent lower than the BAU emissions of 70 $GtCO_2e$ per year. Emissions would then be 30 percent lower than the levels that prevailed in 2005, and about 10 percent below 1990 emissions. This is without accounting for potential rebound effects, which we have not modeled. A rebound effect, for instance, would be if resources freed up by energy savings would be used for alternative, potentially high-carbon consumption.

**Exhibit 3.0.1**

**Global GHG abatement cost curve beyond business-as-usual – 2030**




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

The cost curve shows a high degree of fragmentation among individual abatement options, but there are three major categories of measures:

- **Energy efficiency (opportunity of 14 $GtCO_2e$ per year in 2030).** There are a large number of opportunities to improve the energy efficiency of vehicles, buildings, and industrial equipment, thereby reducing energy consumption. More fuel-efficient car engines, better insulation of buildings, and efficiency controls on manufacturing equipment are just a few of the possibilities. If all energy efficiency opportunities identified in our model were captured, annual growth in global electricity demand between 2005 and 2030 would be reduced from 2.7 percent per year in the case of BAU to about 1.5 percent.[18]

18 Electricity demand annual growth increases back to 2.0 percent when taking additional electricity demand from carbon capture and storage (CCS) and transport into account.

- **Low-carbon energy supply (opportunity of 12 $GtCO_2e$ per year in 2030).** There are many opportunities to shift energy supply from fossil fuels to low-carbon alternatives. Key examples include electricity production from wind, nuclear, or hydro power, as well as equipping fossil fuel plants with carbon capture and storage (CCS), and replacing conventional transportation fuel with biofuels. If these low-carbon alternatives were to be fully implemented, we estimate that they have the potential to provide about 70 percent of global electricity supply by 2030 compared with just 30 percent in 2005;[19] and that biofuels could provide as much as 25 percent of global transportation fuel by 2030. This would constitute a major shift in global energy supply. Several of these low-carbon energy technologies are too expensive today to deploy on a large scale without financial incentives, emphasizing the need to provide sufficient support to make them travel down the learning curve if policy makers want them to contribute to abatement on a big scale.[20]
- **Terrestrial carbon – forestry and agriculture (opportunity of 12 $GtCO_2e$ per year in 2030).** Forests and soils act as natural sinks for carbon. Halting ongoing tropical deforestation, reforesting marginal areas of land, and sequestering more $CO_2$ in soils through changing agricultural practices would increase carbon sequestration. This would lead to negative net emissions of $CO_2e$ into the atmosphere from these sectors in the period we have studied (implying that more carbon is stored than is released from these sinks), a major abatement opportunity versus the BAU in which deforestation continues. However, capturing these opportunities would be highly challenging. More than 90 percent of them are located in the developing world, they are tightly linked to the overall social and economic situation in the concerned regions, and addressing the opportunities at this scale has not before been attempted. Our estimate of the feasibility and cost of this opportunity is therefore subject to significant uncertainty. We also note that terrestrial carbon opportunities are temporary in nature because the sinks would saturate between 2030 and 2050, so that, at the end of this period, there would be few additional areas of marginal land left available for re-forestation.

What comes beyond the €60 per $tCO_2e$ on the cost curve? We estimate that another 3–6 $GtCO_2e$ per year of technical abatement opportunities in these three categories are available at a cost of between €60 and €100 per $tCO_2e$. This range of higher cost of abatement has not been the focus of our research, and the level of uncertainty in our estimates is much higher than for the lower cost opportunities. It is clear, however, that in many of the sectors there is a breaking point where abatement increases in complexity and cost. In the *land-use based sectors* this breaking point is reached when all currently unused and marginal land is being used. Pushing afforestation beyond this point quickly becomes more expensive as the land value quickly increases for land that is productively used today. As a result, we do not assume any additional Forestry potential between €60 and €100 per $tCO_2e$. In Agriculture, there are some opportunities in this cost range, e.g., feed conversion and intensive grazing. In *heavily infrastructure-dependent sectors*, a similar breaking point occurs when all opportunities to change the specification of new infrastructure to low-carbon are exhausted. Additional emission reduction then requires retrofitting existing infrastructure, or alternatively retire existing infrastructure before the end of its lifetime. The costs of both types of opportunity typically increases quickly as younger infrastructure gets retired or older infrastructure gets retrofitted. Still, there are early retirement and retrofit opportunities at a cost of €60 and €100 per $tCO_2e$ in both the Power and Industry sectors. There are also some specific technologies in this cost range, e.g., the gasification of biomass or membrane separation in Petroleum and Gas. In *consumer-related sectors*, all new infrastructure in Transport and Buildings is already addressed at

19 This would include renewable sources (wind, solar, hydro, biomass, geothermal, tide and wave), nuclear, as well as fossil fuels with CCS.

20 We have only included technologies in our curve that we see as technologically proven, that could credibly have costs lower than €60 per $tCO_2e$ abated in 2030, and that we can envisage having a major abatement impact by 2030. There are also many technologies that did not pass our criteria to be included in the curve since they are too early in their development stage, but that could also have a major impact in the period after 2030.

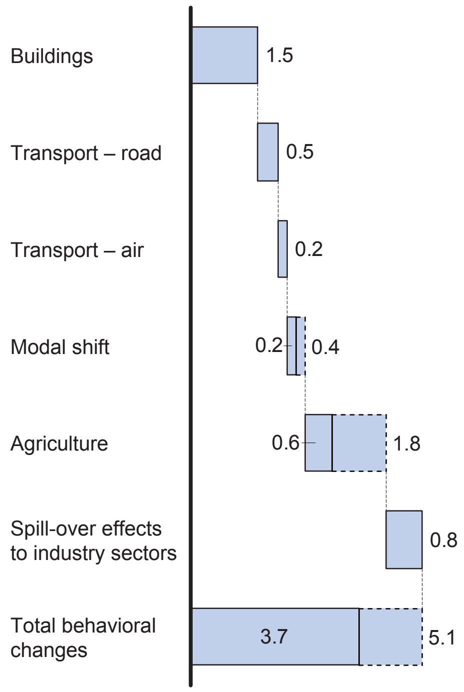
costs below €60 per $tCO_2e$, and we do not assume the early retirement of assets owned by individual consumers. However, selected more aggressive assumptions could be made in the penetration of Building levers at higher cost: higher penetration of passive housing, additional retrofitting of commercial building envelopes, increased penetration of solar water heating and the large-scale rollout of geothermal heat pumps. For Transport, electric vehicles and increased penetrations of hybrids for passenger cars, and hybrids for commercial vehicles could increase abatement. Pushing biofuels even further would involve upgrading engines to allow for a higher biofuels share, thus make it a higher cost option. Finally, in the *waste sector* there is no further potential, given full penetration of recycling and composting of waste at a cost of less than €60 per $tCO_2e$.

An additional abatement opportunity is behavioral change. In an optimistic case – and there is a high degree of uncertainty in these estimates – this could yield between another 3.5 $GtCO_2e$ and 5 $GtCO_2e$ per year of abatement in 2030. Key opportunities include reducing business and private travel, shifting road transport to rail, accepting higher domestic temperature variations (reducing heating/cooling), reducing appliance use, and reducing meat consumption. Changing behavior is difficult, and the abatement realized would depend heavily on whether, and to what extent, policy makers establish effective incentives. Exhibit 3.0.2 shows some illustrative examples of possible changes in behavior – and their emissions impact – without any judgment on whether these behavioral changes should be incentivized or not.

**Exhibit 3.0.2**

## Examples of behavioral changes beyond technical abatement measures

$GtCO_2e$ per year; 2030




**Illustrative calculation assumptions**

- -2°C change in HVAC, i.e., -12% energy use
- -20% for residential water heating; lighting; appliances
- -20% floor space for new builds

- Consumers: smaller cars, driving more efficiently, driving less
- Commercial transport: increased vehicle capacity or utilization, improved route planning, etc.

- -20% air travel

- -5-10% road transport by switching to rail, bus, walk or cycle

- Meat consumption for developed world -20%; ROW -10% (after 40% consumption increase towards 2030)
- Replace 0-50% consumption of ruminants** with other meat

- Cement: -15% (buildings)
- Iron & Steel: -10% (buildings); -5% (transport)
- Chemicals: - 5% (buildings); -5% (transport)

* Behavioral effects accounted for after implementation of all other levers.
** Beef/cattle, sheep, goats
Source: Global GHG Abatement Cost Curve v2.0

**Comparing Versions 1 and 2 Global GHG Cost Curves**

The world has changed significantly in the two years since the publication of the first version of our Global Cost Curve in early 2007. Economic growth has accelerated in the developing world, raising the average annual GDP growth forecast from 3.2 to 3.6 percent; climate change science has advanced, resulting in calls for even more stringent emissions reductions to restrict temperature increases; energy prices have risen, a long-term trend according to the International Energy Agency; and technology has developed. In the mean time, McKinsey has deepened its knowledge of GHG cost curves with the publication of seven national cost curves in collaboration with various industry associations, companies and institutions.

Our updated research incorporates all these elements. The key differences in results between the first version of the cost curve and the curve that we present in this study are

- For 2030, BAU emissions have increased from 58 to 70 $GtCO_2e$ per year globally, primarily due to higher expected economic growth
- The total identified abatement potential has increased to 38 $GtCO_2e$ per year in 2030 (up from 27 $GtCO_2e$), largely due to the higher BAU emissions and the higher cost cut-off (€60 per $tCO_2e$ in version 2 compared to €40 per $tCO_2e$ in version 1), but also due to an number of new insights over the last two years: The main contributors to the increased abatement potential are the Power sector with +4 $GtCO_2e$ per year, mainly from a higher baseline (+ 2 $GtCO_2e$ per year), higher potential from early retirement and a more positive view on renewables growth potential; and Agriculture with about +3.5 $GtCO_2e$ per year with carbon sequestration levers now fully included in the analysis. In the Forestry sector, the assessment is now based on a simplified but explicit bottom-up modeling and abatement potential has increased by little more than +1 $GtCO_2e$ per year.
- These two counteracting effects lead to similar emissions after abatement at 32 $GtCO_2e$ per year
- The average cost of abatement stays relatively constant; up from €2 to €4 per $tCO_2e$ with higher energy prices assumptions** counteracting the higher cut-off cost

* We went from analyzing 6 World regions to 21, with each G8+5 country modeled separately

** Version 1 relied on IEA's World Energy Outlook (WEO) 2005 for its oil price forecast ($40 per barrel), while version 2 relies on WEO 2007 (oil price forecast of $60 per barrel)

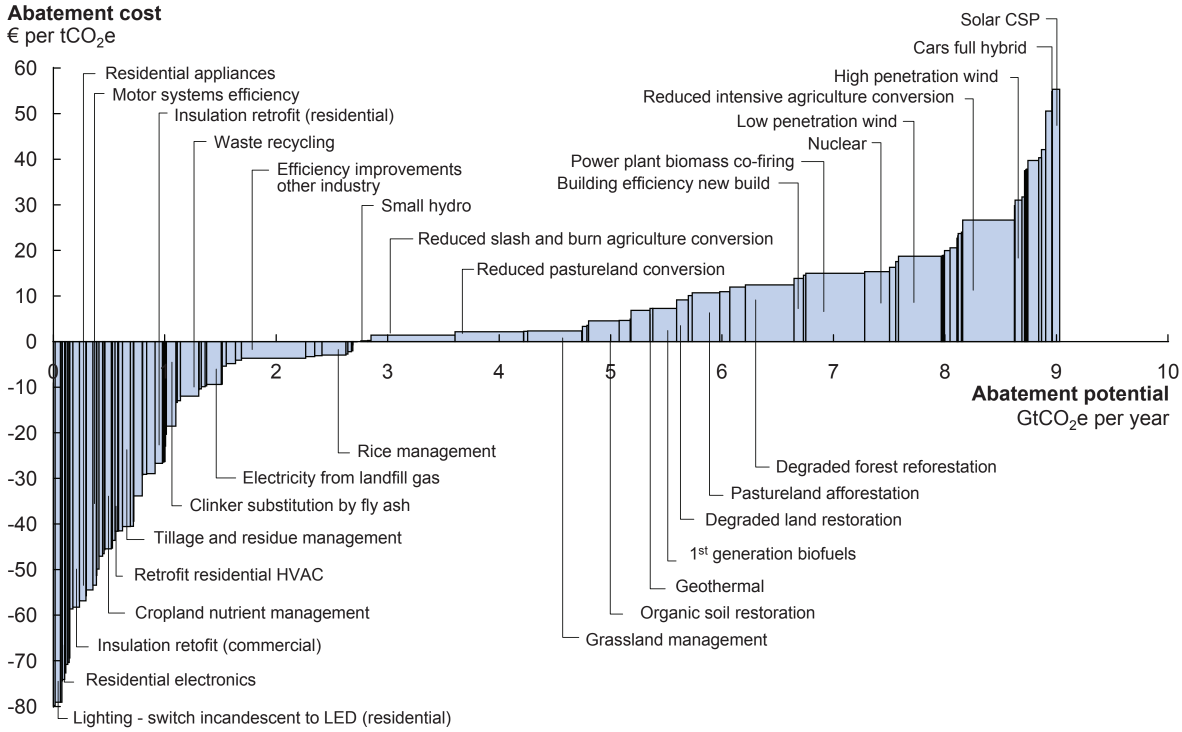
## What could be done until 2015?

This report looks at abatement in a 2030 time frame, reflecting our belief that mitigation action requires a long-term outlook to prioritize different opportunities effectively. As explained earlier, the 2030 cost curve displays the abatement potential from different opportunities if each is successfully pursued in the period from 2010 to 2030, and the weighted average cost over the 2010 to 2030 time period of each opportunity. But what does the curve look like in a shorter time horizon? Exhibit 3.0.3 shows the global 2015 curve. The horizontal axes of this curve represents the abatement potential from each opportunity, if it was successfully pursued in the 2010 to 2015 time period, and the cost is the weighted average cost in the same time period.

What are the big differences between the 2015 and the 2030 curves? First, the overall abatement volume clearly is much lower – around 9 $GtCO_2e$ per year. In fact, it grows in an approximately linear manner over time.

**Exhibit 3.0.3**

## Global GHG abatement cost curve beyond business as usual – 2015




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

Second, the proportional contribution of the sectors differs significantly, with approximately 50 percent of measures related to changes in land use (Forestry and Agriculture), reflecting that these opportunities can be ramped up relatively faster than solutions that have a substantial infrastructure component such as Buildings (which account for only 7 percent of abatement potential in 2015 versus 9 percent in 2030) and Power (18 percent versus 26 percent in 2030). In the case of the latter, most of the potential stems from biomass co-firing, which can very easily be ramped up in existing coal-fired power plants.[21] The contribution of industry stays stable at 19 percent from 2015 to 2030.

Third, emerging technologies such as solar and CCS do not yet contribute substantial abatement volumes and are still expensive given their early stage of development. In the Power sector, as an example, emerging technologies contribute less than 2 percent of total abatement in 2015 at an average cost of €60 per $tCO_2e$. In 2030, that share increases to 11 percent and costs plummet to €28 per $tCO_2e$.

21 Without co-firing, the power share would be only 11 percent of the total abatement opportunity in 2015

## 3.1 Sector view: Three types of sectors with different characteristics

Our research examined abatement measures across 10 sectors. The detailed perspectives per sector are available in the appendix of this report. In this section, we summarize the overall observations from a sector perspective. From an emissions perspective, there turn out to be three categories of sectors, with very different abatement characteristics, and therefore very different implementation challenges (Exhibits 3.1.1 and 3.1.2):

1. **Energy-supply and Industrial sectors (about 17 $GtCO_2e$ per year opportunity, 20 to 55 percent reduction from 2030 BAU).** Emissions in this category are released into the atmosphere from a relatively small number of large point sources, such as power plants, petroleum refineries, steel mills and chemical plants. Emissions are concentrated to the developed world, China and India. Abatement opportunities typically consist of energy efficiency, shifting fuels, or shifting to low-carbon alternatives when building new infrastructure. In some sectors, for instance the Power sector, a significant share of the 2030 opportunity resides in technologies that need to improve their cost competitiveness considerably. The companies in these industries are comparatively large and used to making investment decisions based on regulatory incentives.

   Looking at the available abatement potential, there are opportunities to reduce emissions in these sectors by approximately 17 $GtCO_2e$ per year in 2030 – 45 percent of the total abatement potential in our cost curve. This abatement corresponds to a 20 to 55 percent reduction from the 2030 BAU, depending on the sector. For the Power and Petroleum and gas sectors, this means a reduction of 15 to 60 percent compared to 2005 – when accounting for the demand reduction from consuming sectors in addition to the abatement potential within each sector. For the industrial sectors emissions would still increase by 30 to 60 percent, as the underlying sector growth rates are very high.

   In terms of challenges to achieve the abatement potential, we see them primarily being around technology (scaling up emerging technologies and making travel down the learning curve), around cost, and around avoiding competitive distortions due to different regulation between sectors and countries.

2. **Consumer related sectors – Transport, Buildings and Waste sectors (approximately 8 $GtCO_2e$ per year opportunity, 25 to 90 percent reduction from 2030 BAU).** Emissions in these sectors come from literally billions of small emitters – individual houses and vehicles. Geographically, the opportunities are spread between the developed and the developing world. Abatement opportunities are to a very high degree related to energy and fuel efficiency, and many of them hold a net economic benefit if the impeding agency and other issues could be overcome.

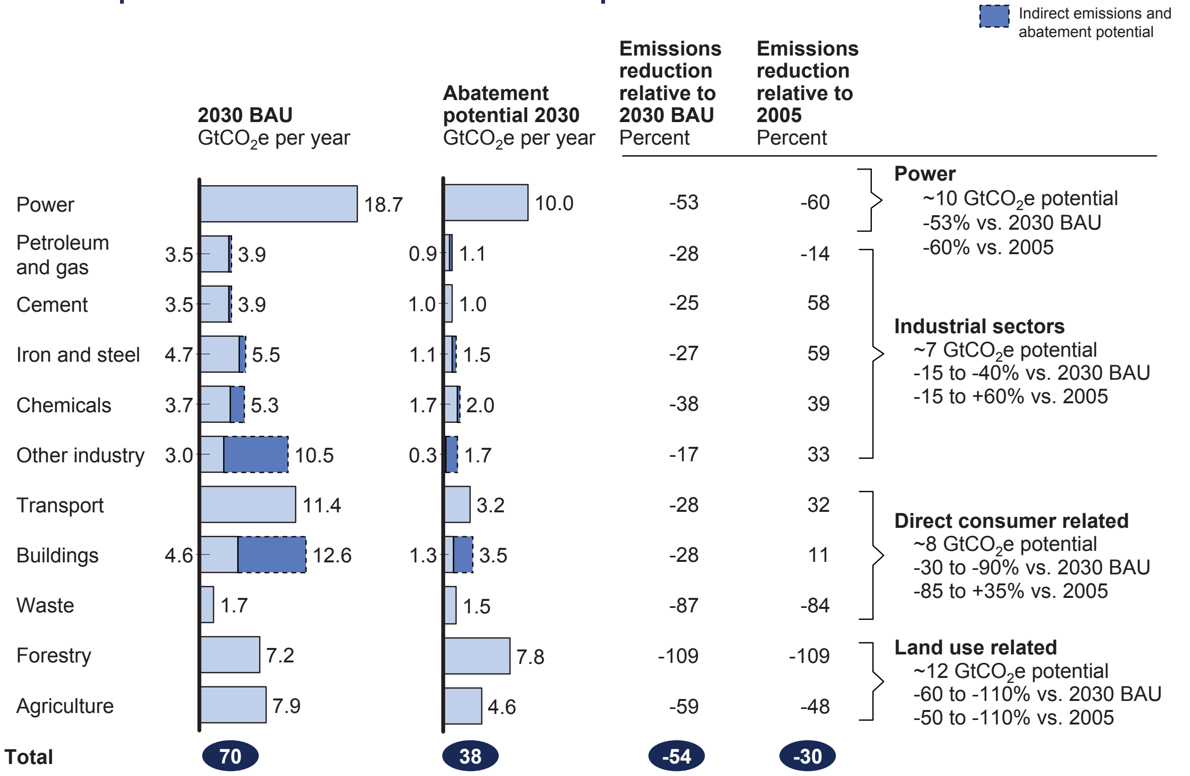
   The overall abatement potential is 8 $GtCO_2e$ per year in 2030 – 22 percent of the total abatement potential in our cost curve. This abatement corresponds to 25 to 90 percent of the 2030 BAU for each sector. Relative to 2005, emissions would still increase by ~30 percent in the Transportation sector and ~10 percent in the Buildings sector, due to the high underlying growth, whereas it would decrease by 90 percent in Waste.

   The implementation challenge in these sectors is primarily to design effective policy to get access to the energy efficiency opportunities. This typically involves policy to overcome the frequent agency and awareness issues in these sectors.

3. **Terrestrial carbon – Forestry and Agriculture sectors (some 12 $GtCO_2e$ per year opportunity, 60–110 percent reduction from BAU)**. Emissions in Forestry come from deforestation and peat; in Agriculture, from livestock and fertilizer use. In both cases the emissions come from billions of small sources, mainly concentrated in the developing world; for Forestry specifically in tropical rainforest regions. These emissions are difficult to measure and monitor, so the uncertainty is high even in the baseline emission estimates.

**Exhibit 3.1.1**

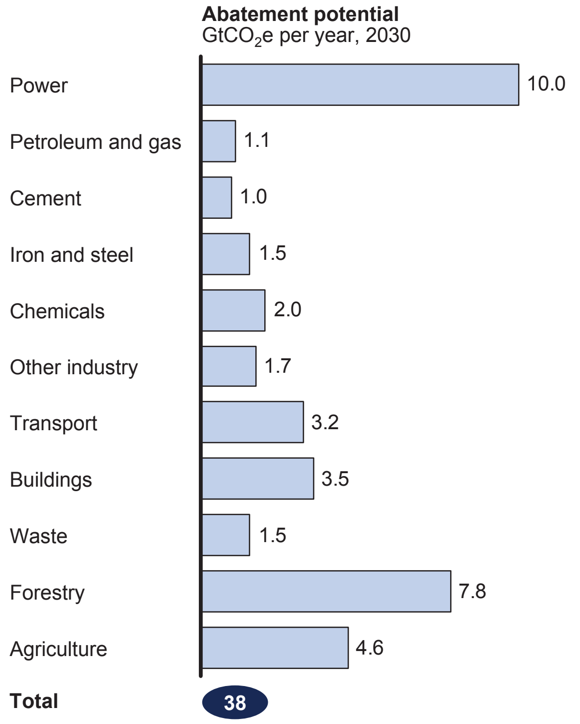
## Sector split – BAU emissions and abatement potential




Source: Global GHG Abatement Cost Curve v2.0

**Exhibit 3.1.2**

## Abatement potential by sector and key levers




| Key levers | Abatement potential |
|---|---|
| • Renewables (Solar, wind, biomass) | 4.0 |
| • Nuclear | 2.0 |
| • CCS | 1.7 |
| • CCS | 0.4 |
| • Energy efficiency | 0.3 |
| • Clinker substitution | 0.5 |
| • Alternative fuels | 0.3 |
| • Energy efficiency | 0.5 |
| • Co-generation | 0.3 |
| • CCS | 0.4 |
| • Motor systems | 0.3 |
| • ICE improvement, hybrids, EV | 1.9 |
| • Biofuels | 0.5 |
| • New build efficiency packages | 0.9 |
| • Lighting and lighting controls | 0.7 |
| • Waste recycling | 0.9 |
| • Land fill gas direct use | 0.2 |
| • Avoided deforestation | 3.6 |
| • Afforestation/reforestation | 2.4 |
| • Grassland management | 1.3 |
| • Organic soil restoration | 1.1 |

Note: This is an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

The key abatement measures in Forestry sector are avoiding deforestation, reforestation, afforestation, and improved forest-management practices.[22] For Agriculture four categories of abatement levers have been identified: land restoration (e.g., re-establishing high water tables to avoid decomposition); cropland management (including crop rotation, cover crops, tillage reduction, nutrient management); pastureland management (e.g., increased grazing intensity); and livestock management.

The total Forestry abatement potential has been estimated at 7.8 $GtCO_2e$ per year in 2030 – corresponding to approximately 110 percent of 2030 BAU emissions[23]. In Agriculture, we see the potential to abate 4.6 $GtCO_2e$ per year in 2030, leaving emissions 60 percent lower than BAU in 2030 and about 50 percent lower than in 2005.

The uncertainty about the abatement potential in both sectors is much higher than for the other sectors given the great implementation challenges. Deforestation projects are notoriously difficult to make effective and there are significant problems of leakage, as well as in measurement and monitoring. In Agriculture, educating and mobilizing billions of farmers around the world to change their daily practices is similarly challenging. Capturing abatement in these sectors would directly impact billions of people, primarily in developing countries, requiring to successfully handle social change and building institutional capacity at the same time.

## 3.2 Regional view: Three types of regions with different characteristics

The abatement potential varies considerably between regions and countries, both in relative and absolute terms (Exhibit 3.2.1). Three major drivers explain the differences: the sector split of a country's economy, the carbon intensity starting point of each sector in a specific country, and the country's economic growth. On the latter driver, economic growth increases the availability of low-cost abatement opportunities relative to BAU because rapid economic growth typically involves the large-scale building of new infrastructure, which provides more low-cost abatement opportunities than retrofitting existing infrastructure with higher efficiency technologies.

Countries and regions fall into three broad groupings in our cost curve analysis in terms of their abatement potential:

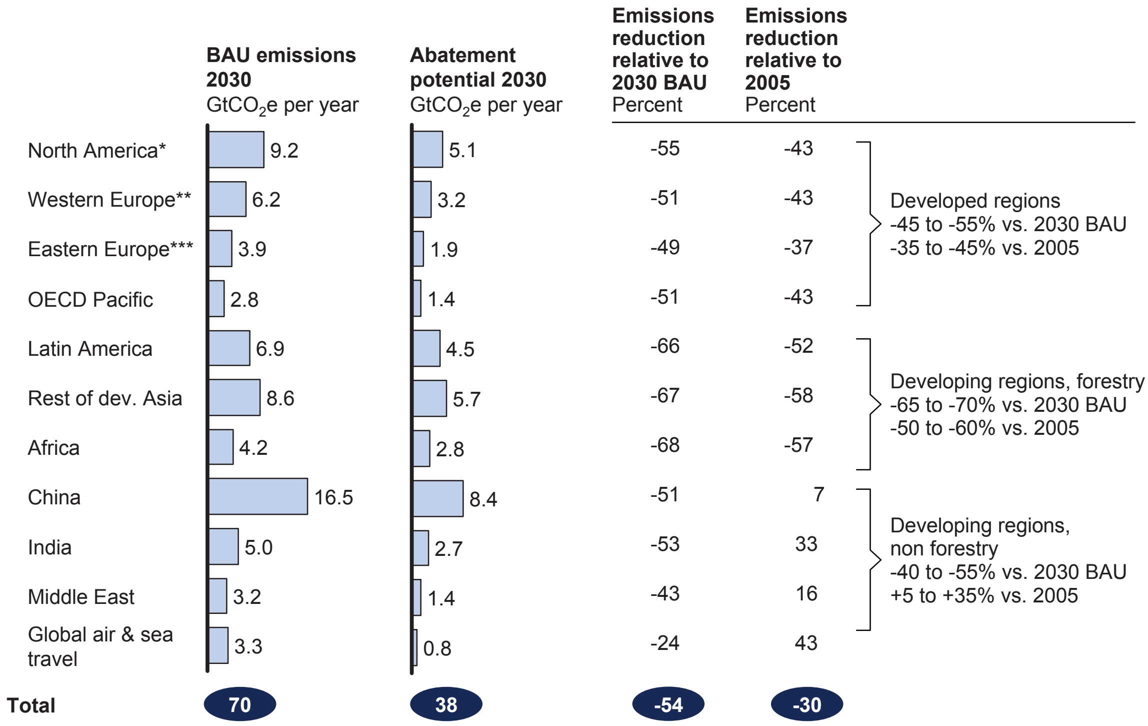
1. **Developed regions (about 12 $GtCO_2e$ per year opportunity, 45–55 percent reduction from 2030 BAU).** Emissions in developed regions accounted for 18 $GtCO_2e$ in 2005, an amount that grows at 0.8 percent per year to reach 22 $GtCO_2e$ in 2030 in the BAU case. Developed regions can typically reduce their emissions by 45 to 55 percent of the BAU level in 2030, which is equivalent to a 35 to 45 percent reduction from the 2005 emissions level. The overall abatement potential in developed countries is 12 $GtCO_2e$ per year in 2030 – 31 percent of the total abatement potential in our cost curve.
2. **Developing Forestry regions (some 13 $GtCO_2e$ per year opportunity, 65–70 percent reduction from 2030 BAU).** Developing regions with very large forest areas accounted for 15 $GtCO_2e$ of emissions in 2005, growing at 1.1 percent per year to reach 20 $GtCO_2e$ in 2030 in the BAU case. These regions can typically reduce their emissions by between 65 and 70 percent of BAU in 2030.

22 Reforestation means planting forest over degraded land with no food or feed production value. Afforestation means planting forest over marginal pastureland and marginal cropland. No assumptions have been made about reforesting or afforesting land with major food or feed value

23 A value over 100 percent means a net reforestation, i.e. that more carbon is stored in Forests than is released

**Exhibit 3.2.1**

## Regional split – BAU emissions and abatement potential




* United States and Canada
** Includes EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, Switzerland
*** Russia and non-OECD Eastern Europe
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; UNFCCC; US EPA

This would leave emissions between 50 and 60 percent lower than levels in 2005. The large abatement potential is due to the fact that the opportunity for abatement in the Forestry sector is above 100 percent (i.e., it is possible to reforest/afforest larger areas than are being deforested by 2030), and because Forestry accounts for up to 50 percent of total 2030 BAU emissions in countries such as Brazil and Indonesia. Without Forestry abatement opportunities, overall emissions would only be about 30 percent lower than 2030 BAU, and some 15 percent less than 2005 emissions. The overall abatement potential in developing Forestry regions is 13 $GtCO_2e$ per year in 2030 – 35 percent of the total abatement potential in our cost curve.

3. **Developing non-Forestry regions (approximately 12 $GtCO_2e$ per year opportunity, 40–55 percent reduction from 2030 BAU).** These regions represented 11 $GtCO_2e$ in 2005 growing at 3.3 percent per year to reach 25 $GtCO_2e$ in 2030 in the BAU case. These regions, which include countries such as China and India, can typically reduce emissions 40 to 55 percent compared to BAU in 2030. However, rapid economic growth still mean that 2030 emissions after abatement would be between 5 and 35 percent higher than 2005 emissions. The overall abatement potential in these regions is 12 $GtCO_2e$ per year in 2030 – 33 percent of the total abatement potential in our cost curve.

If we split the abatement potential in 2030 by regions, we find that two-thirds of the total opportunity (67 percent) is available in the developing world, and about one-third (31 percent) in developed countries. The remaining 2 percent is in global air and sea transport, which is not attributed to individual countries. The reasons for this split are that a large share of 2030 BAU emissions come from the developing world (64%), but also because the emissions in the developing world unproportionally come from the Forestry and Agriculture sectors with a high relative abatement potential. Looking at the split in terms of regions, 49 percent of the potential resides in Asia, 25 percent in the Americas, 14 percent in Europe, and 12 percent in the rest of world. This distribution starkly demonstrates the importance of a global effort to reduce emissions at the lowest-possible cost, regardless who pays for these reductions.

Turning to per capita emissions, we find that these evolve very differently in different regions of the world in BAU, and show only minor convergence after abatement measures are implemented (Exhibit 3.2.2). In developed countries, BAU per capita emissions would rise from 13.7 $tCO_2e$ per capita in 2005 to 16.1 $tCO_2e$ per capita in 2030, a compound annual growth rate of 0.7 percent. With abatement, emissions per capita can be reduced to 7.7 $tCO_2e$ per capita in 2030. In developing countries with a significant share of forestry – our second grouping – BAU emissions would decrease from 6.2 $tCO_2e$ in 2005 to 5.8 $tCO_2e$ per capita in 2030, a 0.2 percent annual rate of decrease. Abatement would bring this value down to 1.9 $tCO_2e$ per capita in 2030. In "other developing countries", including India and China, BAU emissions would grow from 4.0 $tCO_2e$ per capita in 2005 to 7.4 $tCO_2e$ per capita in 2030, an annual rise of 2.4 percent. A level of 3.7 $tCO_2e$ per capita can be achieved in 2030 by pursuing abatement measures. It is noteworthy that, in BAU, some developing countries (e.g., China) would have higher per capita emissions than the developed world (e.g., Western Europe) by 2030. The remaining differences between regions after abatement measures have been taken reflect remaining differences in lifestyles (e.g., floor space in the typical house per person; distance travelled per person and year). Our research concentrates only on what can be done to reduce emissions from levers that do not affect the lifestyle of individuals, and therefore have not assumed any convergence of lifestyle beyond what is already assumed in the BAU.

**Exhibit 3.2.2**

## Emissions per capita development

$tCO_2e$ per capita per year

| | 2005 | 2030 BAU | 2030 emissions after abatement | Reduction relative to 2030 BAU Percent | Reduction relative to 2005 Percent |
|---|---|---|---|---|---|
| North America* | 22.2 | 23.0 | 10.3 | -55 | -53 |
| Western Europe** | 9.4 | 10.7 | 5.3 | -51 | -44 |
| Eastern Europe*** | 13.7 | 19.3 | 9.8 | -49 | -29 |
| OECD Pacific | 11.9 | 14.7 | 7.2 | -51 | -40 |
| Latin America | 8.9 | 9.7 | 3.3 | -66 | -63 |
| Rest of dev. Asia | 6.4 | 6.5 | 2.2 | -67 | -66 |
| Africa | 3.5 | 2.8 | 0.9 | -68 | -74 |
| China | 5.8 | 11.3 | 5.6 | -51 | -3 |
| India | 1.6 | 3.4 | 1.6 | -53 | 0 |
| Middle East | 8.2 | 10.9 | 6.2 | -43 | -24 |
| **Global** | 7.1 | 8.6 | 3.9 | -54 | -45 |

* United States and Canada
** Includes EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, Switzerland
*** Russia and non-OECD Eastern Europe
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; UNFCCC; US EPA

### 3.3 Brief outlook to 2050

As explained above, emissions would need to decrease by 35 to 50 percent in the period from 2005 to 2030 to attain a pathway likely to achieve the 2 degrees Celsius threshold, according to the IPCC authors we have consulted. As the world economy is set to double during the same time period, this implies almost quadrupling the global carbon productivity (measured as the amount of GDP output per unit of emissions) or 5 to 7 percent of annual improvement on annual basis, compared to a 1.2 percent increase in the business-as-usual development. Our bottom-up research has confirmed that such an improvement is possible – but challenging – on a 2030 time horizon.

If current climate-science estimates hold true, we will again need to repeat a similar carbon productivity improvement in the period from 2030 to 2050: emissions again need to decrease by approximately 50 percent, whereas the global economy will presumably grow considerably. While our bottom-up work has not focused on this time period, it does provide one important observation: If the pace of improvement in global carbon productivity that was possible between 2020 and 2030 – 5.7 percent per year – can be maintained in the 2030 to 2050 period, this would get the world economy to emission levels very close to those required according to current climate science.

# 4. Energy savings could largely pay for upfront abatement investments

The question of how much tackling climate change is going to cost is a recurrent issue in today's global discussion about how to transition to a low-carbon economy. How large will capital investments need to be? Which sectors offer the highest returns on those capital outlays? Answering such questions is one of the main objectives of our research and our analysis allows us to assess not only the cost but also the opportunity of investing in carbon abatement. Many of the measures we have identified can be captured at a relatively low cost and many would even produce a positive net return. In aggregate, our research indicates that future energy savings compensate for a huge share of the initial investments of an ambitious abatement drive, if the most cost-effective abatement options are pursued. It also demonstrates how much can be saved through policy that incentivizes the lowest cost alternatives. As mentioned in previous chapters, this is not to say that the implementation of such an abatement program will be easy. On the contrary, as described in Chapter 3, it will require a significant mobilization challenge to capture the opportunities that we have identified. It is also likely that shortfalls in realizing the low cost options will mean that higher cost alternatives will have to be pursued. There will also be transaction and program costs as well as dynamic macro-economic effects that we have not included in our analysis.

In order to bring clarity to the issues of costs and investments, we use two financial measures – the abatement cost and the abatement investments – each of them shedding a specific light on the economics of climate change.

- The abatement cost reflects the annualized cost of different abatement measures in a given year per tonne of carbon saved compared with the business-as-usual technology[24]. This metric allows us to compare the economic attractiveness of different abatement measures.
- The upfront investments represent the additional capital expenditure in the year when the abatement action is taken, relative to the business-as-usual investment.

24 The abatement cost is a weighted average across sub-opportunities, regions, and years, and is calculated as the sum of incremental capital expenditures (annualized as a repayment at an interest rate of 4 percent) and incremental operational expenditures or savings.

### 4.1. Abatement cost

An overview of the net costs and benefits of all the technical abatement measures on the cost curve shows that some 30 percent of the measures would produce a net economic benefit and that another 50 percent would involve costs of below €20 per $tCO_2e$. The average cost of the abatement opportunities along our cost curve is approximately €4 per $tCO_2e$, making the total cost to implement the 38 $GtCO_2e$ per year on the 2030 curve approximately €150 billion per year in 2030. This is an optimistic cost estimate, both because it assumes opportunities would be addressed in perfect order according to their cost, and each would be captured to its full extent and because it excludes transaction and program costs.

The reason we have chosen to exclude transaction and program costs from our analysis is that these reflect political choices how to implement different measures and vary from case to case. Therefore, they cannot be incorporated into the cost curve in an objective way. Take the case of the abatement potential in energy-efficient light bulbs. Policy makers could either mandate the use of energy-efficient bulbs (less expensive, but intrusive) as the Australian government has chosen to do, or they could try to convince consumers to switch voluntary through education campaigns (more expensive, but less intrusive), as some European governments have opted to do. The transaction and program costs vary considerably in the two cases.

Transaction and program costs also have a high degree of inherent uncertainty, as programs of the size now being discussed have not been tried before, e.g., in Forestry. The external sources we have looked at to understand the order of magnitude of the these costs often estimate them between from below €1 per $tCO_2e$ to €5 per $tCO_2e$[25], again with big variations across sectors. Using this range to illustrate the order of magnitude of the total transaction and program costs, it translates to a cost of between €40 billion per year and €200 billion per year in 2030 for the 38 $GtCO_2e$ per year of abatement opportunities we have identified. This would make the total global cost €200–350 billion annually by 2030, which corresponds to approximately 0.4 percent of the forecasted 2030 global GDP.

An alternative approach would be to value the opportunities with net economic benefits at zero, arguing, as some economists would, that transaction and program costs for these opportunities are so large that they compensate any apparent net gain. This approach makes the average cost approximately €12 per $tCO_2e$, and the total cost around €450 billion in 2030.

All of those cost estimates correspond to less than 1 percent of forecasted global GDP by 2030. They are optimistic in the sense that they assume that the lowest cost options are addressed first. However, they also exclude the dynamic effects of large-scale investments into new infrastructures and technologies, which many believe would have a significant positive effect on the global economy.

If temperatures increase as the IPCC estimates they will in a BAU scenario, one could compare the cost of reducing emissions (frequently called *mitigation* costs) to the so-called *adaptation* costs (i.e., the costs of managing the global warming that would occur if no or limited action was taken to reduce emissions). We have not made any attempt to quantify these adaptation costs, as they rely on a series of climate-science assumptions that are well outside our area of expertise. The IPCC estimates in their Fourth Assessment Report that these costs could be on average 1 to 5 percent of GDP for 4 degrees Celsius of warming – with high variations across the world.[26] Such estimates are uncertain by nature and controversial in the view of climate-change skeptics, who would judge adaptation costs to be much lower than these estimates, or even zero.

25 For example, Lawrence Berkeley National Laboratory; Alston and Hund; Woods Hole Research Center; Conservation Reserve Program; and the United States Department of Agriculture.

26 *Climate Change 2007, Fourth IPCC Assessment Report*, Intergovernmental Panel on Climate Change

When interpreting these costs, the reader should be aware that this report assesses the costs of individual abatement levers from a societal perspective, the aim being to make our analysis of the opportunity as relevant as possible to policy makers and comparable across countries and sectors. The abatement costs that appear in the cost curve are therefore net of taxes and subsidies, and reflect a 4 percent interest rate, in line with typical long-term government bonds. This approach is different from the perspective of private decision makers who often face higher interest rates, taxes, and subsidies (see fact box "Changes in the cost curve in a decision-maker perspective").

**Changes in the cost curve in a decision-maker perspective**

The global cost curve takes a societal perspective, net of taxes and subsidies. This approach serves as a useful starting point for policy makers when they are prioritizing action on GHG abatement and allows for comparisons of the size and cost of abatement opportunities between countries and sectors. However, the societal approach does not reflect the economic investment case faced by those making decisions about whether to capture these opportunities. An institutional, corporate, or individual consumer will each have different interest rates, expected time horizons for repayment, and subject to taxes, tariffs, and subsidies. The cost to the decision maker is therefore often different from the cost shown in the cost curve. The decision maker perspective is better suited for assessing switching costs or estimating $CO_2$ prices that would be necessary to incentivize certain technology investments.

There are three broad categories of abatement levers that incur different directional cost changes from the decision maker's perspective. Levers in Buildings, Power, Industry, Forestry, and Agriculture tend to have higher costs for the decision maker mainly due to higher interest rates in these cases. Levers in Transportation energy efficiency tend to be lower from the decision maker's point of view as fuel taxes increase the value of fuel savings. Finally, some emerging technologies levers can substantially benefit from subsidies, and so we have a lower cost in a decision-maker perspective.

## A large share of abatement opportunities are net profit positive

A large share of the abatement opportunities involves investing additional resources upfront in making existing or new infrastructure more carbon efficient, and then recouping part or all of that investment through lower energy spending in future years. This is the case, for example, with better insulated houses, more fuel-efficient cars, and wind power. This means that the annual abatement cost – the measure we use in our cost curve – is much smaller than the initial capital investment. In fact, if all the technical abatement opportunities at a cost of less than €60 per $tCO_2e$ were to be implemented, we estimate the total additional investment (incremental to BAU) would be €810 billion per year in 2030. The net cost would be only about €150 billion per year.

The energy efficiency opportunities all have this financial profile, as well as many of the renewable energy opportunities. Our analysis shows that there are about 11 $GtCO_2e$ per year of abatement opportunities in 2030 – some 30 percent of all measures in the cost curve – where the energy savings actually outweigh the upfront investment, so that these opportunities carry a net economic benefit over their lifetime, even without any additional $CO_2$ incentive. These opportunities with a net economic benefit largely consist of energy efficiency measures in the Buildings and Transport sectors. Moreover, these opportunities have become more profitable in the past few years as a result of high energy prices.

As we highlighted earlier, some economists believe that the transaction and program costs of GHG abatement are so large that opportunities with net economic benefits cannot exist. They argue that markets are always so efficient that these opportunities would be realized or are cost positive. If there are such attractive abatement opportunities, why then have consumers and entrepreneurs not already captured them? Our view is that a range of market imperfections currently act as a barrier and disincentive and hinder some of these opportunities to fully materialize in the business-as-usual, including:

- **Lack of awareness.** In many cases, consumers and businesses are unaware of energy efficiency alternatives and the potential savings they offer. This is sometimes because individual opportunities are small, even while they yield large energy savings in aggregate. One example of this is low-energy lighting, for which there is a good business case in many countries with payback periods of only a few months, but where overall savings are often limited compared with the average household budget.
- **Agency issues[27].** In many opportunities with net economic benefits, the consumer or company reaping the benefits of lower energy bills is not actually making the upfront investment. For instance, construction companies have limited incentives to insulate homes beyond the level required in building codes, since it is to home owners and tenants that the benefits of lower energy bills accrue.
- **Financing hurdles and rapid payback requirements.** The upfront investment itself, particularly in Buildings and Transport, can be a significant barrier; many consumers require their money back in only one to two years to make energy efficiency investments. As a result, appliance makers, for instance, often compete more on shelf price than on energy consumption, and sometimes choose not to include additional energy-saving features in their products even if these pay for themselves over the lifetime of the appliance.

The fact that these opportunities offer a net economic benefit does not mean that they are easy to realize. On the contrary, designing the right policy framework to capture this potential in a cost-effective manner is a significant challenge as it requires finding ways to overcome an array of market imperfections. We discuss regulatory priorities in more detail in Chapter 7.

27 Also referred to as “split incentives”

## 4.2. Abatement investments

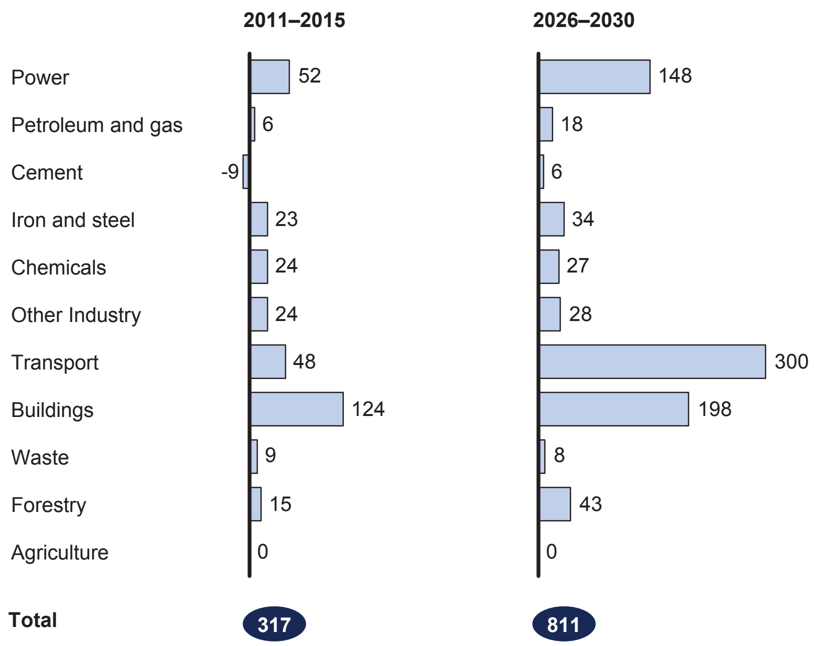
Realizing the abatement potential we have described would require global incremental investments – above and beyond BAU – of €320 billion annually in 2015, increasing to €810 billion per year by 2030. To put these capital requirements in perspective, they correspond to 5 to 6 percent of projected BAU global investments in fixed assets in each respective year. This does not appear to entail a prohibitive financing challenge at the global level. In GDP terms, the investments correspond to 1.3 percent of forecasted global GDP in 2030[28], although the actual impact of these investments on GDP would be highly dependent on how they were financed and whether regions are capital constrained.

Although the financing of abatement does not appear to be prohibitive at a global, aggregate level, there will be significant challenges in different regions and sectors. The investment needed is spread very unevenly with three sectors accounting for 80 percent of the capital required (Exhibit 4.2.1).

**Exhibit 4.2.1**

**Capital investment by sector incremental to business-as-usual for the abatement potential identified**

€ billions per year; annual value in period




Source: Global GHG Abatement Cost Curve v2.0

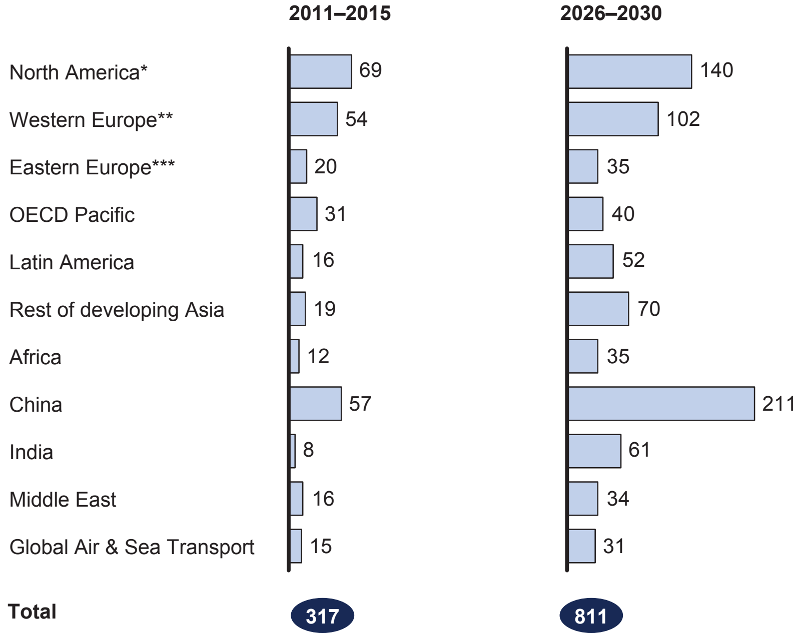
Transport and Buildings account for some 35 percent and 25 percent, respectively, of the total investment needed. These sectors are similar in that they are both consumer-driven and depend on literally billions of investment decisions. Although, investing in fuel-efficient vehicles and energy-efficient houses will often pay for itself over the lifetime of the car or house, finding effective ways to incentivize and finance the additional upfront expenditure may not be easy. A fuel-efficient car often costs between €1,000 and €3,000 more than a model that is less fuel efficient; improving the energy efficiency of a residential house between €5,000 and €10,000. New models for consumer finance will likely be necessary. The Power sector accounts for another 20 percent of the total capital required, as

28 Global GDP is projected around $90 trillion by 2030 and we use an exchange rate of 1.5 USD/EUR throughout our analysis

**Exhibit 4.2.2**

**Capital investment by region incremental to business-as-usual for the abatement potential identified**

€ billions per year; annual value in period




* United States and Canada
** Includes EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, Switzerland
*** Russia and non-OECD Eastern Europe
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; UNFCCC; US EPA

most technologies here involve significantly higher upfront capital costs than today's BAU coal and gas plants. The rest of the investment required comes largely from industrial sectors.[29]

In terms of regional investment needs, three regions stand out: China with annual investment of €211 billion in 2030, North America with €140 billion per year, and Western Europe with €102 billion per year (Exhibit 4.2.2) – representing 55 percent of total global investment. In all three regions the majority of the investment is required to capture the large abatement opportunity in Buildings and Transport, which is driven by the huge asset base in these sectors. When comparing investment needs with GDP, the shares differ substantially: Whereas the investment in developed countries only represents 0.5 to 1.0 percent of GDP, in developing countries this ratio increases to 1.2 to 3.5 percent of GDP. It should be noted here again that the actual impact of these investments on GDP would be highly dependent on how they were financed and whether regions are capital constrained.

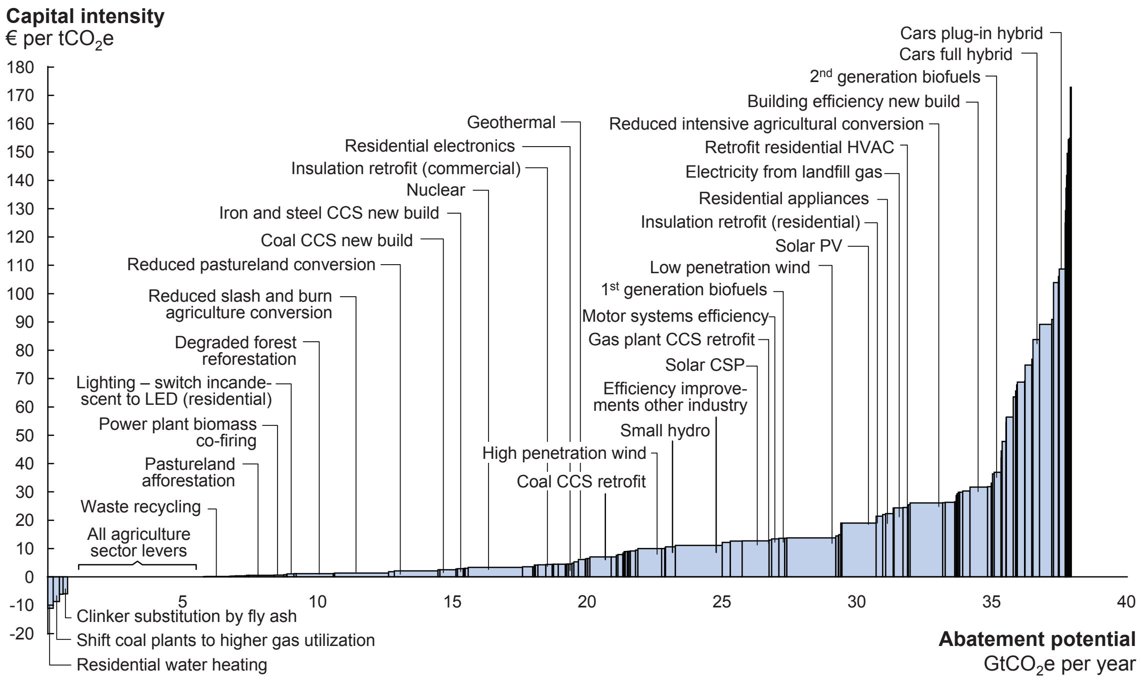
29 It is worth noting two specific features of our methodology. We assume that Forestry requires a significant amount of capital investments as all avoided deforestation measures are realized by covering the opportunity cost through an initial fund, e.g., buying the land to be protected. In cement, incremental investment compared to BAU is negative due to the fact that the substitution of clinker by other alternatives (e.g. fly ash) significantly reduces investment requirements in clinker production capacity and more than compensates for CCS and other capital investments.

## Capital intensity and the prioritization of abatement action

If we turn to an analysis of the capital intensity[30] per abatement opportunity, we find that about half of the measures we have identified have a capital intensity of below €5 per $tCO_2e$ and three-quarters of the opportunities have an intensity of below €15 per $tCO_2e$. It is interesting to observe that the order between opportunities in the capital curve is very different from the order in the cost curve. For instance, many energy-efficiency opportunities that appear on the left-hand side of the cost curve end up much further to the right in the capital curve (Exhibit 4.2.3)[31].

**Exhibit 4.2.3**

### Capital intensity by abatement measure




Source: Global GHG Abatement Cost Curve v2.0

As the cost curve is the more economically rational way to prioritize abatement opportunities – taking into account not only upfront investments but also the resulting energy savings – the capital curve demonstrates that different priorities could emerge in a capital-constrained environment. Investors might choose to fund the opportunities with the lowest capital intensity rather than the lowest cost over time. This could make the cost of abatement substantially higher over time.

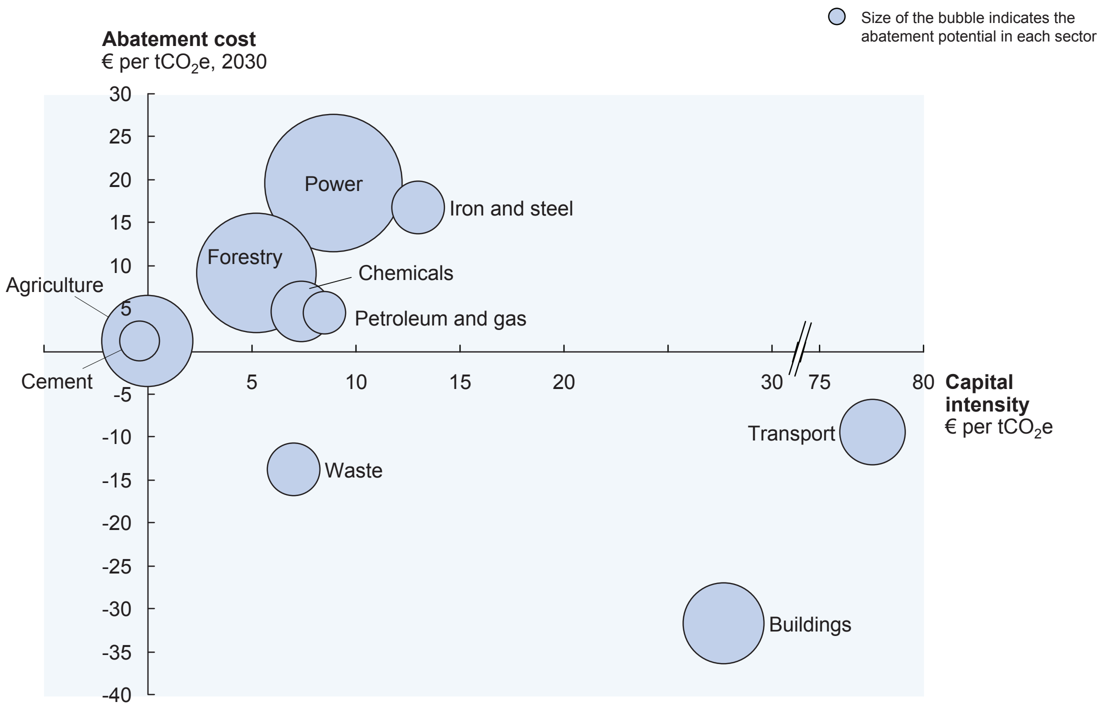
30 We define the capital intensity of an abatement measure as the additional upfront investment relative to the BAU technology, divided by the total amount of avoided emissions over the lifetime of the asset . For a more fuel efficient car, for instance, the capital intensity would be calculated as the additional upfront investment compared to the BAU technology, divided by the amount of $CO_2$ saved through lower fuel consumption during the lifetime of the car. The main difference with abatement cost is that the capital intensity calculation does not take financial savings through lower energy consumption into account.

31 Negative capital intensity occurs if the abatement measure requires less capital than the BAU. One example is clinker substitution in the Cement sector, where investments in new build clinker production plants would be reduced, if the share of clinker substitutes in cement is increased.

Comparing the abatement cost and abatement investments shows that the implementation and funding challenges will be very different across sectors (Exhibit 4.2.4). We can discern several groupings that share themes in common. For instance, in Transport and Buildings, upfront financing might be challenging but the cost is actually low once investments have been made. Waste is a clear win-win with both low capital intensity and attractive returns. Power has one of the higher average abatement costs but has a comparatively low capital requirement given the large amounts of emissions saved. Industrial sectors show a similar profile to Power with efficiency opportunities dampening the impact of levers such as CCS. Making the abatement happen in Power and Industry is likely more a question about compensating companies for the high costs, than it is about financing the investments. Finally in Forestry and Agriculture, both costs and investments are relatively low. Here, the implementation challenges are practical rather than economical, namely, designing effective policy and an effective way of measuring and monitoring the abatement.

**Exhibit 4.2.4**

## Capital intensity and abatement cost




Source: Global GHG Abatement Cost Curve v2.0

# 5. The importance of time

## 5.1 The effect of delaying abatement action

If the world wants to set itself on an emissions pathway with a high probability of containing global warming below 2 degrees Celsius, taking action is urgent. The window for an effective response to climate change is relatively narrow – explicitly, the next five to ten years. The urgency of the task is not just about forgoing an opportunity to reap emissions savings in a single year or short span of years. Moreover, by not acting promptly, the world would lock itself into high-carbon infrastructure for several decades to come.

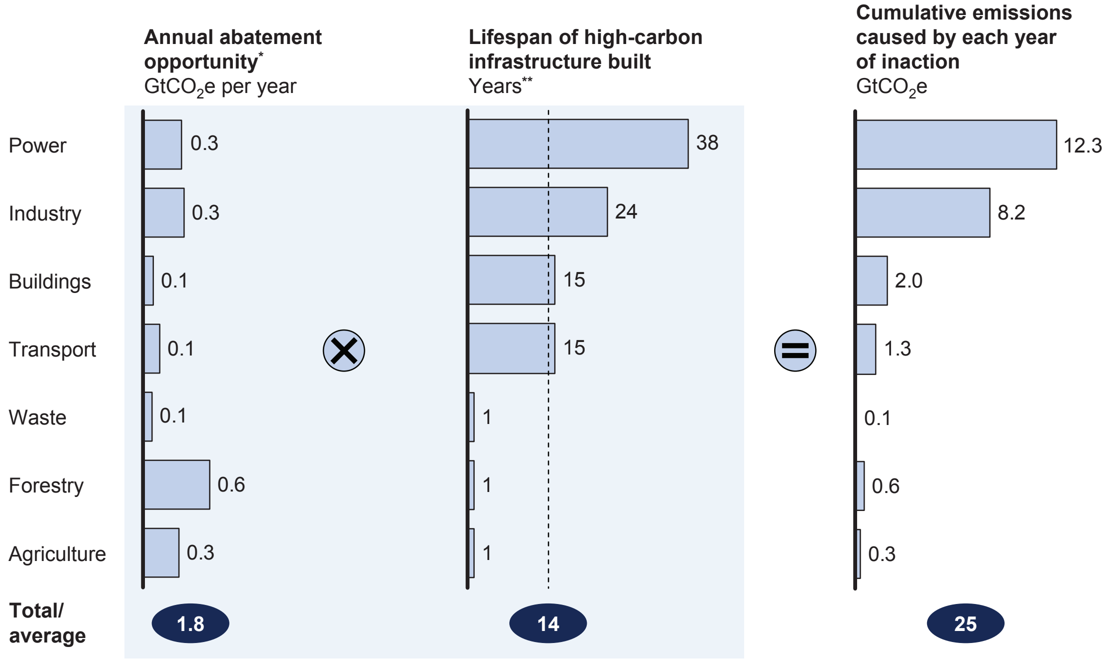
If we look at the impact of one single year of delaying abatement, we estimate that this would cause 1.8 $GtCO_2e$ of additional emissions globally in that year (Exhibit 5.1.1). The emissions would simply grow according to the BAU development instead of declining. What's more, during this year of delay, high-carbon infrastructure with long lifetimes would be built. In our assessment, the average effective lifetime of infrastructure is 14 years, but with a broad range: Coal fired power plants often have a lifespan of 40–50 years, many industrial plants of 20–30 years, and vehicles typically 10–20 years.

The result of this lock-in effect is that one year of delay – in addition to the foregone abatement opportunity of 1.8 $GtCO_2e$ in that year – commits the world to 25 $GtCO_2e$ of cumulative emissions over the following 14 years.

Turning to a delay of 10 years from 2010 to 2020, we find that there would be three major impacts. First, the potential abatement in 2030 would fall from 38 to 22 $GtCO_2e$ per year, a reduction of 40 percent. Second, such a delay would result in a cumulative lost abatement opportunity of some 280 $GtCO_2e$ by 2030 compared with action taken in 2010. This is comparable to 21 times combined 2005 US and China emissions. Finally, the lock-in effect due to a 10-year delay would continue for decades beyond 2030, especially in the case of long-lived carbon-intensive infrastructure in the Power, Industry, and Building sectors. (Exhibit 5.1.2)

**Exhibit 5.1.1**

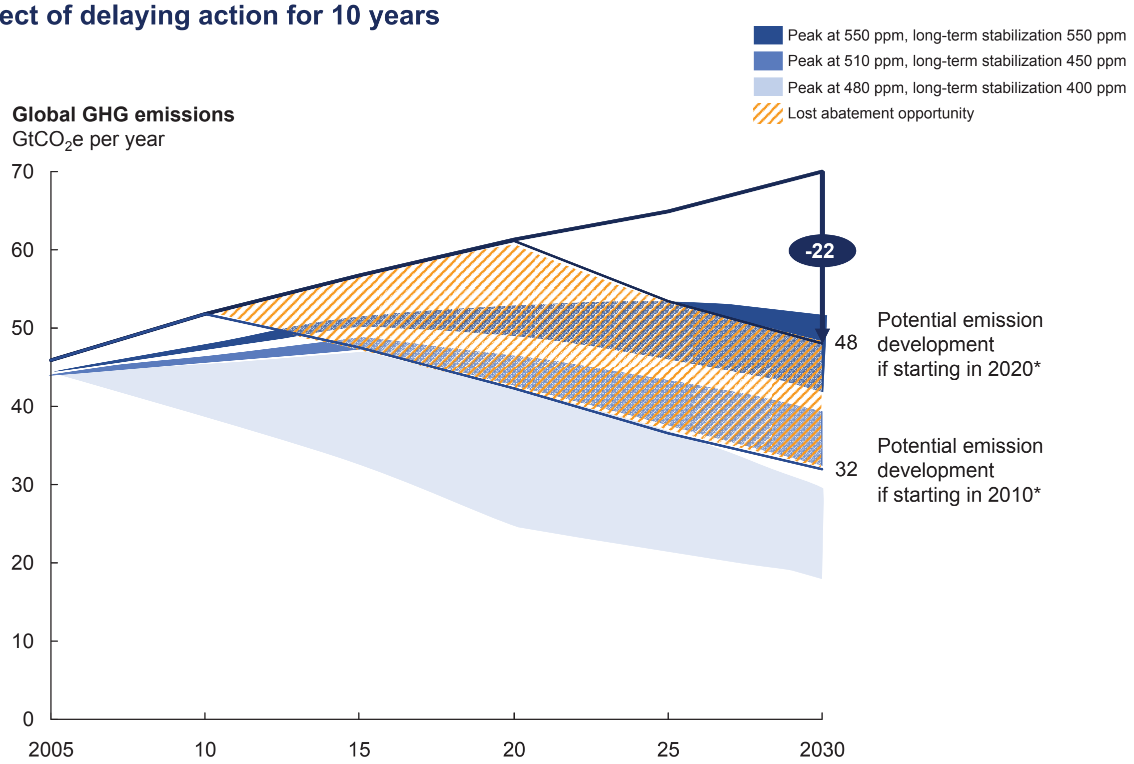
## Lock-in into high-carbon infrastructure




* Annual between 2010–15; calculated as emission difference between BAU and emissions after abatement.
** Weighted average of lifespan of carbon-intensive assets or infrastructures in each sector.
Source: Global GHG Abatement Cost Curve v2.0

**Exhibit 5.1.2**

## Effect of delaying action for 10 years




* Technical levers <€60/$tCO_2e$
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; OECD; EPA; den Elzen; van Vuuren, Meinshausen

In greenhouse gas concentration terms, the effect of the 10-year delay is that the atmosphere would end up a on 550 ppm emissions pathway, even if aggressive action was taken in 2020. The world would end up at the high end of the 480 ppm pathway if similarly aggressive action was taken in 2010. As a rule of thumb, one could conclude that each year of delay or inaction leads to a 5 ppm higher expected peak GHG concentration level.[32]

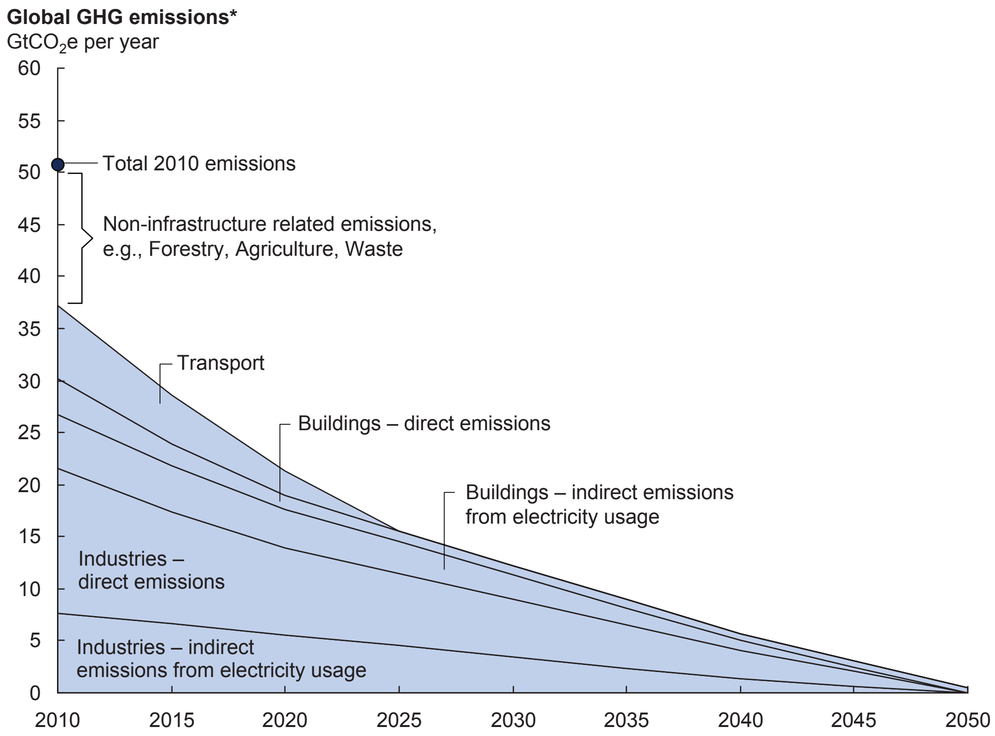
## 5.2 The importance of new infrastructure choices

It is critical to the effort to abate GHGs that those making infrastructure choices employ low-carbon options. About three-quarters of today's emissions are infrastructure-related, including much of the emissions from Buildings, Transportation, Power and Industrial sectors. Infrastructure is long-lived and today's capacity will only be phased out over the next 50 years, making it inevitable that the transition to a low-carbon economy will take time (Exhibit 5.2.1).

Retrofitting existing capacity – whether power plants or buildings, for instance – is far more costly than building new infrastructure with low-carbon (and energy efficient) technologies. As a result, we see that more than 50 percent of the opportunities in the cost curve relate to making the right new infrastructure choices when building new infrastructure. Only about 15 percent of the abatement potential in the cost curve comes from retrofitting existing assets to reduce their carbon intensity, with the remaining 35 percent of the curve not being infrastructure-related at all (Exhibit 5.2.2).

**Exhibit 5.2.1**

### Existing infrastructure phase-out projection

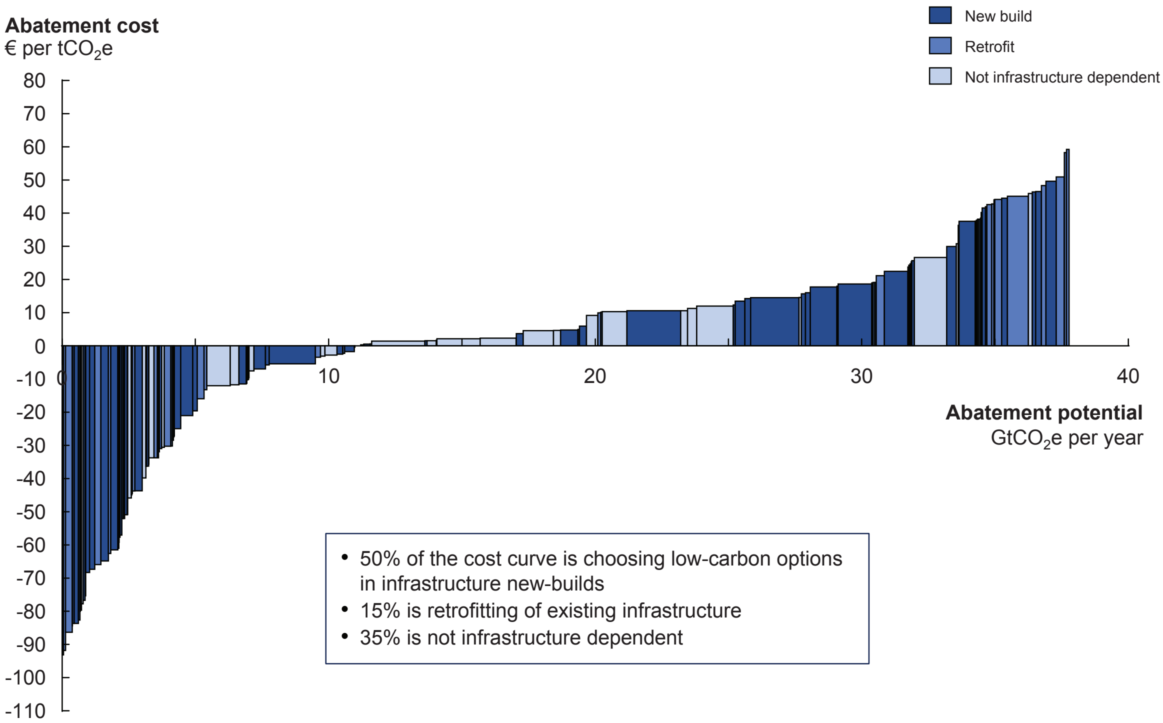



* 2005 total emissions were 46 GtCO2e.
Source: Global GHG Abatement Cost Curve v2.0

32 The effect of a 10-year delay is that 2030 emissions end up in middle of the stabilization path that peaks at 550 ppm, instead of at the high end of the path that peaks at 480 ppm. Rounding the difference to 50 ppm (to account for the fact that emissions end up in the middle of the 550 ppm scenario and the high end of the 480 ppm scenario) makes the effect 5 ppm per year.

**Exhibit 5.2.2**

## The role of infrastructure choices along the cost curve




Source: Global GHG Abatement Cost Curve v2.0

# 6. Scenarios and sensitivities

## 6.1 Integrated implementation scenarios

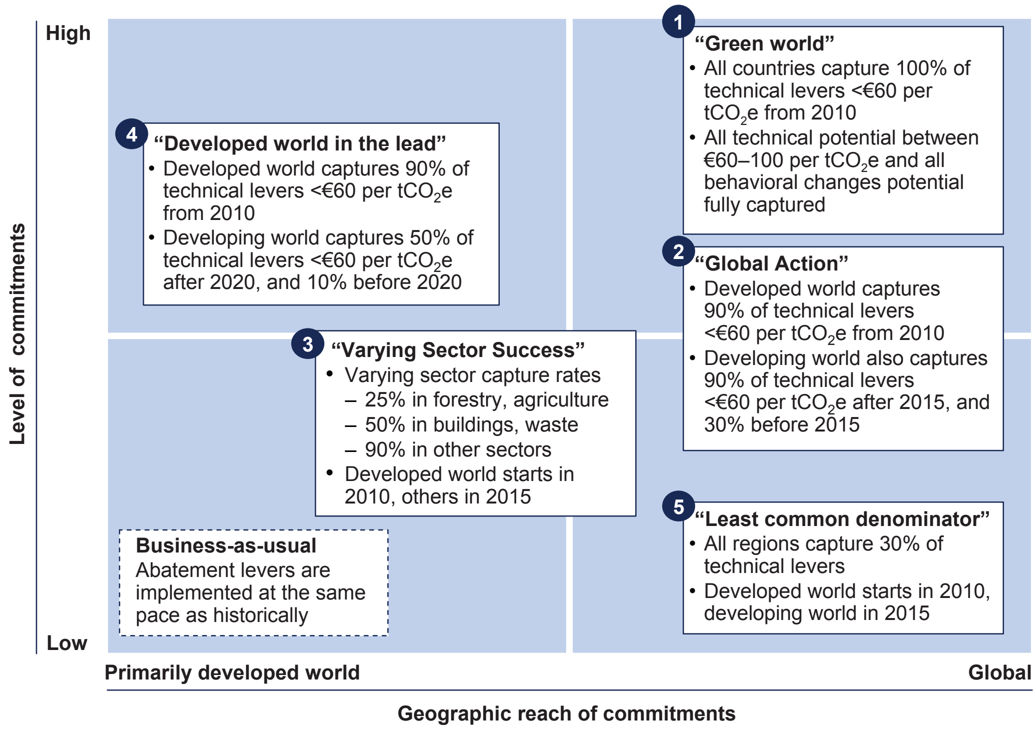
The abatement opportunities that we have outlined in this report are all potentials, i.e., they represent a best case if each opportunity is pursued to its maximum economic potential below €60/t$CO_2$e, and the implementation is successful globally. Some opportunities are more challenging and costly than others. In this chapter, we start to think about the effects of possible implementation leakages. We outline a set of illustrative, integrated implementation scenarios along the two dimensions of geographic reach and level of emissions reductions. These scenarios are intentionally simplified compared with the highly complex global policy discussions currently underway, since our objective is to illustrate the order-of-magnitude implications of different, conceivable global policy choices. None of the scenarios that we describe imply a recommendation about what policy is preferable.

We have developed five overall implementation scenarios (Exhibit 6.1.1). Taking these together, the overall conclusion we reach is that swift and concerted global action to reduce emissions is necessary if the world is to establish a pathway that leads to a high probability of limiting global warming to 2 degrees Celsius. If any one of the major sectors or regions do not take action, it will be very difficult for the rest of the world to make up the difference. Three out of five scenarios show substantial increases in emissions – of between 7 and 30 percent in the years between 2005 and 2030 – that would put the world on emission pathways consistent with temperature increases of 3 degrees Celsius or more (Exhibit 6.1.2).

1. **The Green World scenario** represents the most concerted global approach to reducing carbon emissions. In this scenario, all regions would start implementing their full technical abatement potential in 2010 and also opportunities to reduce emissions through behavioral changes and levers between €60 per t$CO_2$e and €100 per t$CO_2$e would be captured in all regions. Developed world emissions would be 60 percent lower in 2030 than 2005 levels while developing world emissions would be about 50 percent lower. Overall investment needs are expected to be higher than €850 billion per year by 2030, which is required to achieve full potential of technical levers below €60 per t$CO_2$e. This is a highly optimistic and highly challenging scenario from a implementation point of view – as it assumes all opportunities are successfully captured across regions and sectors – but it would best position the world to limit global warming to 2 degrees Celsius, as it leads to a 480 ppm peak pathway.

**Exhibit 6.1.1**

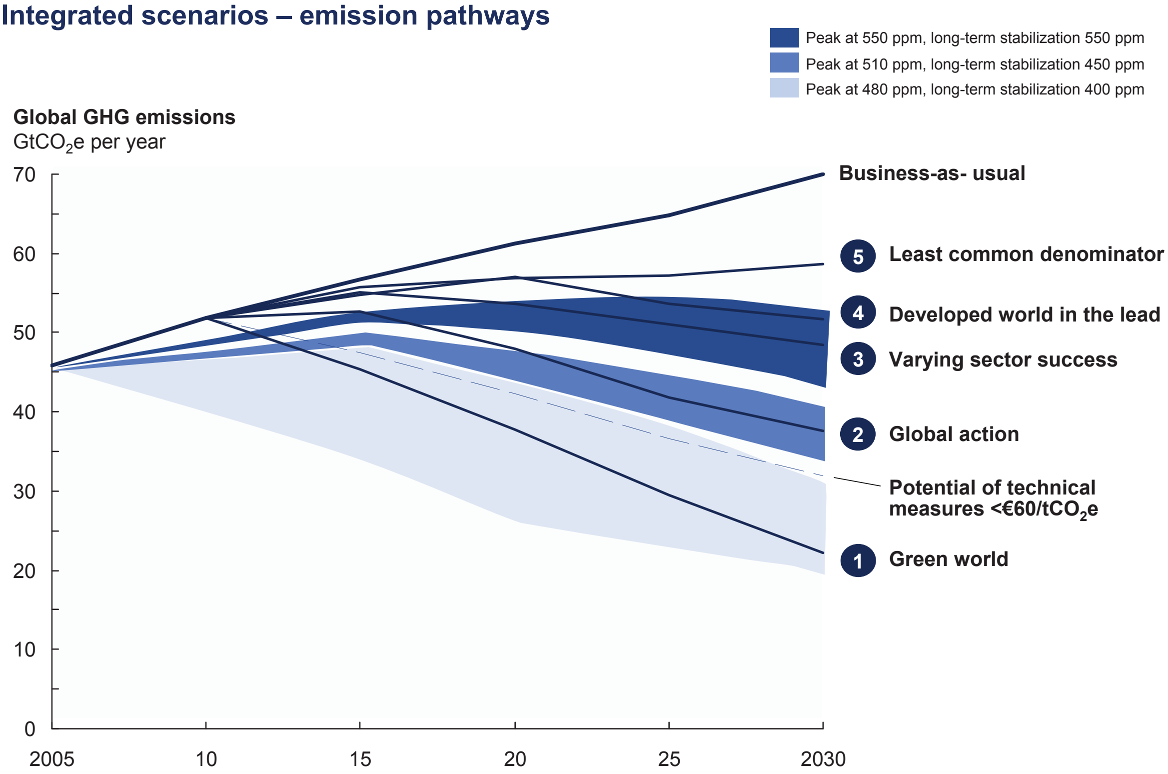
## Integrated implementation scenarios 2010–2030




Source: Global GHG Abatement Cost Curve v2.0

**Exhibit 6.1.2**

## Integrated scenarios – emission pathways




Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; IPCC; den Elzen; Meinshausen; OECD; US EPA; van Vuuren

2. **Global action** assumes aggressive global commitment to capture the technical opportunities costing less than €60 per $tCO_2e$ but does not assume the capture of any more expensive technical opportunities or any behavioral changes. In this scenario, the developed world captures 90 percent of the abatement potential starting in 2010, assuming a certain implementation leakage. We assume that the developing world captures 30 percent of the abatement opportunities between 2010 and 2015, largely energy-efficiency-related measures financed by, for instance, the Clean Development Mechanism. Starting 2020, the share of opportunities captured in the developing world is assumed to increase to 90 percent. In this scenario, developed world emissions would be 40 percent lower in 2030 than 2005 levels, and developing world emissions would be about 5 percent below. Overall investment needs is expected to €710 billion per year by 2030. This scenario leads to a 510 ppm peak scenario pathway.
3. **Varying sector success** assumes that, while all nations agree to tackle climate change jointly, implementation in several key sectors proves highly challenging. The developed world takes the lead, starting abatement in 2010, the rest of world soon follows suit in 2015. The success of implementation varies across sectors globally. While 90 percent of the abatement potential in Power, Transport, and Industrial sectors is achieved (sectors with a high regulatory feasibility), only 50 percent of the opportunities in Buildings and Waste are realized. The Forestry and Agriculture sectors – where effective regulations are notoriously challenging to put in place – see an even lower adoption rate of 25 percent. In this scenario, the developed world would reduce 2030 emissions to 30 percent below the 2005 level, but emissions in developing regions would be some 30 percent above the 2005 level. Overall investment needs is expected to €590 billion per year by 2030. This scenario would leave the world on a 550 ppm peak pathway.
4. **Developed world in the lead** assumes that the developed world implements 90 percent of the technical opportunities from 2010. The developing world would achieve only 10 percent of their abatement potential between 2010 and 2020, and then implement 50 percent of their potential between 2020 and 2030. Developed world emissions would be some 40 percent below the 2005 level while developing country emissions would increase by about 50 percent from 2005 to 2030. Overall investment needs is expected to €440 billion per year by 2030. This scenario would also leave the world on a 550 ppm peak pathway.
5. **Least common denominator** assumes that all nations agreed to participate in a coordinated global regulatory framework, but that abatement targets are set at comparatively low reduction levels. This scenario assumes that the developed world takes action in 2010 and the developing world in 2015. All regions achieve only 30 percent of their abatement potential. Developed world emissions in 2030 would be at the same level as in 2005, while emissions in developing countries would be about 50 percent above 2005 levels. Globally, this scenario would lead to emissions being about 30 percent above 2005 levels in 2030. Overall investment needs is expected to €250 billion per year by 2030. This scenario would lead to a pathway above the 550 ppm pathway scenario.

The five scenarios that we have outlined demonstrate that to meet or stay below the 2 degrees Celsius global warming level, concerted action across regions and sectors is required.

## 6.2. Uncertainties and sensitivities

There are, as we have stressed, significant uncertainties both about the impact of different abatement opportunities and their cost. This is unavoidable in any investigation with such a broad scope and long time horizon, and means that our abatement data should be interpreted as directional estimates rather than exact quantifications.

Assumptions of the volume or impact of abatement opportunities in different sectors are highly sensitive to implementation success "on the ground". Agriculture and Forestry could technically provide up to 12 $GtCO_2e$ per year of abatement, but implementation of the abatement measures we include in the cost curve has never been attempted on such a large scale. The same is true for most of the energy efficiency measures we have identified. On the other hand, there could also be technological breakthroughs that could deliver unanticipated abatement potential.

Estimates about the cost of abatement and its investment requirements is highly sensitive to what assumptions we make about energy prices, the rate of future technology developments, and interest rates. We have discussed sensitivities with relation to abatement volumes in the previous section and therefore focus on costs in the following section.

## Abatement economics sensitivity to energy prices

The past year has shown that energy prices can be subject to extreme volatility, with oil prices fluctuating between about $150 and $50 a barrel in the span of less than six months. One perennial question raised in the climate-change debate is whether high energy prices in themselves are not enough to cut emissions. Our study suggests that high energy prices help – but are not enough per se to deliver sufficient reductions in emissions.

It is true that an increase in energy prices reduces the average cost of abatement by making energy efficiency opportunities more profitable and the switch to alternative energy sources cheaper. If we assume an average oil price of $120 per barrel rather than the $60 a barrel price assumed by the IEA in the BAU forecast we use, and that other energy prices increase proportionally, this reduces the average cost of abatement in our model by approximately €19 per $tCO_2e$, equivalent to cutting the total cost of abatement in 2030 by approximately €700 billion annually. As a very rough rule of thumb, increasing oil prices by $10 (€6.7) per barrel cuts average abatement costs by €3 per $tCO_2e$ within the $60–120 per barrel range (Exhibit 6.2.1).[33] In contrast, a low energy-price environment with an oil price of $40 (€27) per barrel results in an increase of average abatement costs of about €4.5. However, increasing energy prices is not a cheap way to reduce emissions, as the energy-price increase would create a wealth transfer from oil users to oil suppliers that is several times higher than the savings in emissions abatement cost.

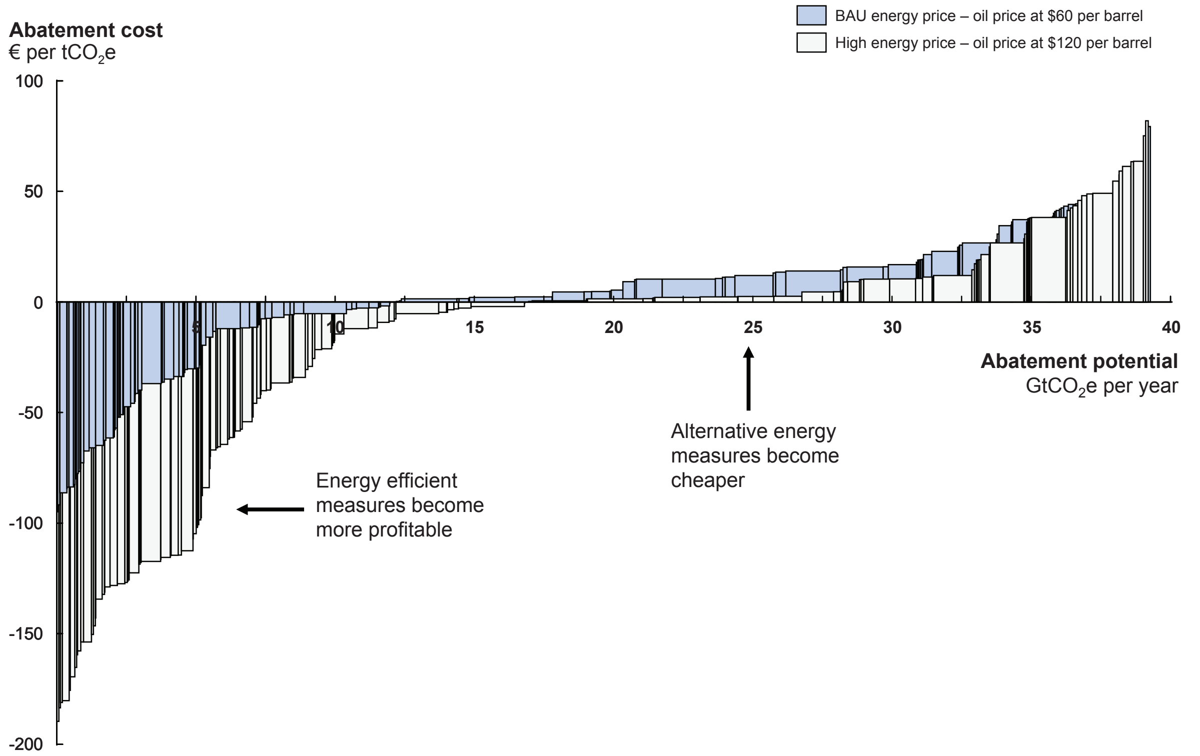
There is another important effect of high energy prices, one that our model does not capture – the impact of high energy prices on energy consumption. However, in a recent study, the McKinsey Global Institute has estimated that an increase in the oil price from $50 a barrel to $70 a barrel would cut global 2020 energy demand by as little as 1.1 percent, everything else equal. There are two reasons for this limited effect. First, oil-price changes only have an impact on a small proportion of the range of energy prices paid by end users, due to regulated, subsidized, or heavily taxed end-user prices. Second, high oil prices accelerate GDP growth and therefore energy demand in oil-exporting countries, where oil tends to be subsidized and energy productivity is low.[34]

33 Other energy prices increase according to the historic pattern of price correlations between oil, gas, and coal.

34 *Curbing global energy demand growth: The energy productivity opportunity*, McKinsey Global Institute, May 2007 (www.mckinsey.com/mgi).

Exhibit 6.2.1

**Effect of high energy prices (oil price at $120 a barrel)**




Source: Global GHG Abatement Cost Curve v2.0

## Uncertainty of future technological development

There is also uncertainty around the future rate of technology improvement, especially for emerging technologies with high expected learning rates. However, even if costs do not decline as rapidly as we assume, the overall effect on the average cost and volume of abatement remains moderate. In the unlikely case of a significant shortfall in learning rates for multiple technologies (we modeled a case in which the learning rates of several key emerging technologies[35] would be only two-thirds of what is assumed in our standard assumptions), average abatement costs increase by less than €3 per $tCO_2e$, and the volume of abatement remains almost constant. While implementation of the affected individual technologies would change significantly, other low-carbon technologies can in many cases partly compensate.

As an example, we have assessed the effect of changing the learning rate[36] of solar PV from 18 to 14 percent. For the base learning rate of 18 percent, power generation costs go down from €180 per MWh in 2005 to €36 per MWh in 2030. With the lower learning rate the costs would only decrease to €53 per MWh and the 2030 abatement cost would increase by €20 per $tCO_2e$. In addition, this has an impact on abatement potential due to merit order effects, which decreases by more than 15 percent. However, the overall results for the Power sector only change slightly because other low-carbon technologies such as wind, biomass and CCS could partly compensate for the lost abatement volume. One exception is the CCS technology. It has a total potential of 3.3–4.1 $GtCO_2e$ per year in 2030. If it

35 Solar PV, Solar CSP, Geothermal, Nuclear, CCS, LEDs, Solar water heaters, Hybrid vehicles

36 Defined as the cost decrease for every doubling of cumulative installed capacity

would not materialize as expected, it would be hard to compensate for, as it is the only technology that can on a large scale address the emissions from existing fossil fuel power plants and respective point source emissions in the industry.

### Capital-intense abatement opportunities are sensitive to interest-rate levels

Our BAU assumes an interest rate of 4 percent, similar to long-term government bond rates. This is because we take a government/societal perspective on the cost of abatement, the idea being that, if a government wanted to incentivize a capital-intense abatement opportunity, it could borrow at the bond rate to do so. Increasing the interest rate boosts capital costs and therefore increases the total cost of abatement. A higher interest rate reflects more closely the situation that decision makers face when making investments, for example based on their company's weighted average cost of capital. Setting the interest rate at 10 percent instead of 4 percent increases the overall cost of abatement from €4 per $tCO_2e$ to about €14 per $tCO_2e$; with an interest rate at 15 percent, the abatement cost rises to €21 per $tCO_2e$. As a rough rule of thumb, average abatement costs increase by approximately €7 per $tCO_2e$ for every 5 percentage points increase in the interest rate. Capital-expenditure-intensive abatement measures such as nuclear, solar, and wind see even higher cost increases.

# 7. Four areas of regulation

Effective policy and regulation will be at the core of the response to global warming. In fact, the transition to a low-carbon economy might be the first global economic transition of this scale to be driven largely by policy. Designing this policy is a huge challenge to political leaders and regulators: it needs to achieve aggressive emission reductions, incorporate many sectors of the economy, be acceptable by many countries, be cost effective, and be equitable among the many stakeholder groups that are concerned.

This study does not take a view of what regulation should be put in place and how aggressively targets should be set. These are political decisions, that need to be made considering all the aspects above, and also considering many non-climate related political priorities. However, our research highlights four categories of abatement opportunities that policy makers should consider to achieve emission reductions at lowest possible cost (Exhibit 7.0.1):

1. **Regulation to overcome the market imperfections that prevent the net-profit-positive opportunities from materializing, e.g. through technical norms and standards.** As described above, there are significant abatement opportunities that already today offer net economic benefits, but still do not materialize due to agency issues and other market imperfections. These opportunities very often relate to energy efficiency, and are largely concentrated in the Buildings, Transport and Industry sectors. To realize them, policy makers need to find a way to overcome the market imperfections, i.e., to align the interests of the large numbers of consumers and companies that need to be involved in making these opportunities come true. This is no easy task, as this type of regulation is often politically sensitive, and often has unwanted side effects such as competitive distortions. Technical standards and norms is one often-used policy instrument, but there are also others.

2. **Establishing stable long-term incentives to encourage power producers and industrial companies to develop and deploy GHG-efficient technologies.** The policy implementation challenges are comparatively limited in these sectors: emissions come from a relatively small number of large point sources that are easy to measure and monitor, companies in these sectors are typically used to making financial decisions based on regulatory incentives, and consumer implications are comparatively small. At the same time, there is a cost attached to most of the abatement action in these sectors. To realize the abatement opportunities, therefore, policy makers need to establish some type of financial incentive to make it attractive for companies to invest in abatement, e.g., in the form of a $CO_2$ price or a $CO_2$ tax.

3. **Providing sufficient incentives and support to improve the cost efficiency of promising emerging technologies.** There are many innovative technical solutions that are promising in terms of having

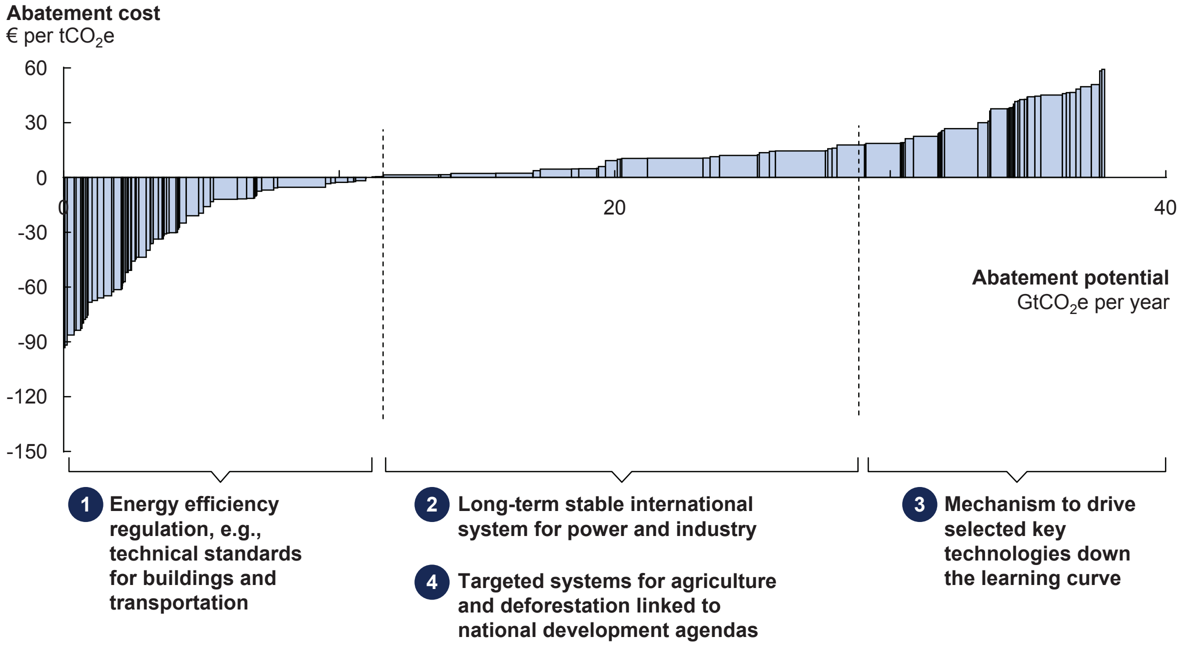
a global impact on reducing emissions in the long term, especially in period between 2030 and 2050. However, these evolving technologies are today too expensive to encourage their development through a carbon price alone. To bring these technologies into play, policy makers need to provide targeted financial support already now so that they can travel down the learning curve and provide low cost abatement solutions in the future.

4. **Addressing the potential in Forestry and Agriculture, primarily located in developing economies, linking abatement to overall development.** It is notoriously difficult to achieve emission reductions in these sectors: the emissions are concentrated in the developing world, they are very disperse among billions of people, they are difficult to measure and monitor, and they are tightly linked to other local development issues such as land ownership. To address these emissions, policy makers will need to design effective local policies that change the work practices of literally hundreds of millions small farmers and forest workers, and that fit within the context of the overall development agenda of the concerned regions. The success of such abatement policies and programs remains highly uncertain, as they have not been tried on this scale before.

Achieving effective regulation in the four above-mentioned areas presents a significant challenge, but also a great opportunity for policy makers to achieving emissions reductions at lowest possible cost.

**Exhibit 7.0.1**

## Key areas of regulation




Source: Global GHG Abatement Cost Curve v2.0

# 8. Sectoral abatement opportunities

## 8.1 Power

The Power industry plays a unique role in climate change, being by far the largest sector both in emissions and opportunities to reduce them. In 2005, power industry emissions were 10.9 $GtCO_2e$ per year, or 24 percent of global GHG emissions. In a BAU projection, emissions are expected to grow to 18.7 $GtCO_2e$ per year in 2030, which would keep the Power sector's share of global emissions approximately constant. This development is driven by a doubling in global electricity demand and by a preference for fossil-based electricity production in many parts of the world. However, there are also many opportunities to reduce emissions. These options fall into four broad categories: renewable energy, CCS, nuclear energy, and demand reductions through energy efficiency. Adding up the potential of these four groups, there is a total emissions reduction opportunity of 12.4 $GtCO_2e$ to 14.4 $GtCO_2e$ per year in 2030. If the full potential were to be captured, power emissions in 2030 would be reduced to 40 to 60 percent below 2005 levels, and there would be a major shift of the global production mix towards low-carbon alternatives. The implementation challenges in the Power sector are largely related to technology: making renewable energy technologies, CCS and nuclear more cost competitive, and increasing their capacity. The fact that so many of the abatement opportunities rely on emerging technologies makes future cost estimates uncertain.

### Business-as-usual emissions

In the BAU case – based on the IEA's *World Energy Outlook 2007* – global power demand grows by 94 percent from 2005 to 2030.[37] The IEA assumes global growth in power generation of 2.7 percent per year, which is closely in line with GDP growth. In developed countries, power demand increases slightly more slowly than GDP; in developing moderately faster than GDP since energy demand increases proportionally more quickly when a country is industrializing. Geographically, North America and China together account for over 40 percent of 2030 power demand. The rest of Asia

37 The BAU development reflects the IEA's view of power generation capacity growth if the policy environment remains as it is today. Our research studies abatement opportunities on top of and relative to this BAU case.

and Western Europe make up another 20 and 14 percent, respectively, of 2030 demand. The BAU case assumes slightly decreasing carbon intensity driven by more efficient plants and by a slight production mix shift towards lower carbon options, resulting in an emissions increase by 72 percent between 2005 and 2030, from 10.9 $GtCO_2e$ to 18.7 $GtCO_2e$ per year. The emissions growth stems primarily from a forecasted continued growth in coal-fired power generation, from approximately 9,450 TWh in 2005, to 16,000 TWh 2030, but also from growth in gas-fired generation (from 5,700 TWh in 2005 to 8,800 TWh in 2030).

## Potential abatement

Emissions abatement in the Power sector is achieved by reducing demand for electricity, or by replacing fossil-fuel power generation with low-carbon alternatives. (see “Abatement methodology in the power model”). To achieve this, there are four key groups of abatement measures (see also Appendix IV for detailed assumptions):

- **Energy efficiency.** Energy efficiency improvements made in electricity-consuming sectors reduces the demand for electricity production compared to the BAU case, which contributes to emission reductions. According to our model, the 2.7 percent annual growth of electricity demand in the BAU would be reduced to 1.5 percent per year if all electricity saving measures were realized in electricity consuming sectors. This efficiency effect is slightly reduced by additional electricity demand for CCS in the industry sectors and electrified vehicles. The total net emissions savings from this is approximately 4.4 $GtCO_2e$ per year in 2030.
- **Renewable energy.** There are many promising renewable energy technologies. The key technologies providing abatement in our model are wind, solar photovoltaics (PV), concentrated solar power (CSP), geothermal, biomass, and hydro. Other renewable power generation technologies, such as wave and tidal power generation, also have potential for emissions abatement, but most researchers agree that these will not contribute significantly to electricity production by 2030.
- **Nuclear energy.** We estimate that the total amount of nuclear power produced could almost double from 2005 to 2030, from ~2,700 TWh to ~4,900 TWh. The reasons why not even more nuclear capacity could be built in a 2030 time frame are the long lead times in nuclear construction, and all the supply chain constraints that the industry will run into when scaling up their installations. These estimates are in line with the volumes the World Nuclear Association assumes in an aggressive build-out scenario.
- **Carbon Capture and Storage (CCS).** Our modeling assumes that this technology – at the demonstration stage today – will prove feasible at a large scale, and will come down to a cost of €30 to €45 per $tCO_2e$ in a 2030 perspective. As such, we estimate that it could have a significant emissions impact – as it is the only currently feasible technology that allows for continued use of coal for power generation, while at the same time reducing emissions substantially. CCS can also be used to address the emissions from large point sources in Iron and Steel, Chemicals, Cement, and Petroleum. We estimate that the combined potential for CCS across Power and these Industry sectors is up to 3.3–4.1 $GtCO_2e$ per year by 2030.

Estimating the impact that each low-carbon technology could have and how its costs could develop is a highly complex topic that depends on the learning rates of different technologies, the development of fuel prices, natural limitations (e.g., average insolation intensity), demand patterns over time, the setup and capacity of the power grid, and many other factors. Our abatement model does not try to capture the

**Abatement methodology in the power model**

The abatement calculations in the power sector were conducted in four stages:

1. For each geographic region in our scope, the aggregated electricity demand from the electricity-using sectors was determined, starting from the IEA's WEO 2007 business-as-usual forecasts, but adjusting for electricity demand reductions from energy efficiency measures, as well as increases; e.g., from electrification of transport.
2. The need to build new electricity production capacity in each geographic region was determined, based on the electricity demand forecast, as well as a simulation of retirements in the existing power plant fleet.
3. Low carbon technologies were ordered in terms of cost competitiveness in each region, using lowest 2030 cost as the criteria, and taking best available information of future learning rates and fuel prices into account. The maximum available volume of each low-carbon technology was also determined, using the assumptions and constraints laid out in "Table A: Key technology assumptions".
4. Each low carbon technology was in the model built out to its maximum potential, in order of increasing cost, until the electricity production capacity gap was filled.

full complexity of power markets, nor does it try to forecast how the power generation mix will develop. Instead, the model examines the *potential* to reduce GHG emissions in the Power sector (assuming required policy is put in place), and it provides estimates of what role different technologies could play and what their cost could be in a global stretch scenario where the ambition would be to reduce emissions to the maximum extent possible.

To illustrate the uncertainty in the impact of different technologies, we have developed two scenarios for the Power sector (Exhibit 8.1.1). Note that these scenarios are not actual development forecasts for 2030 but reflect what is possible if all available options are captured:

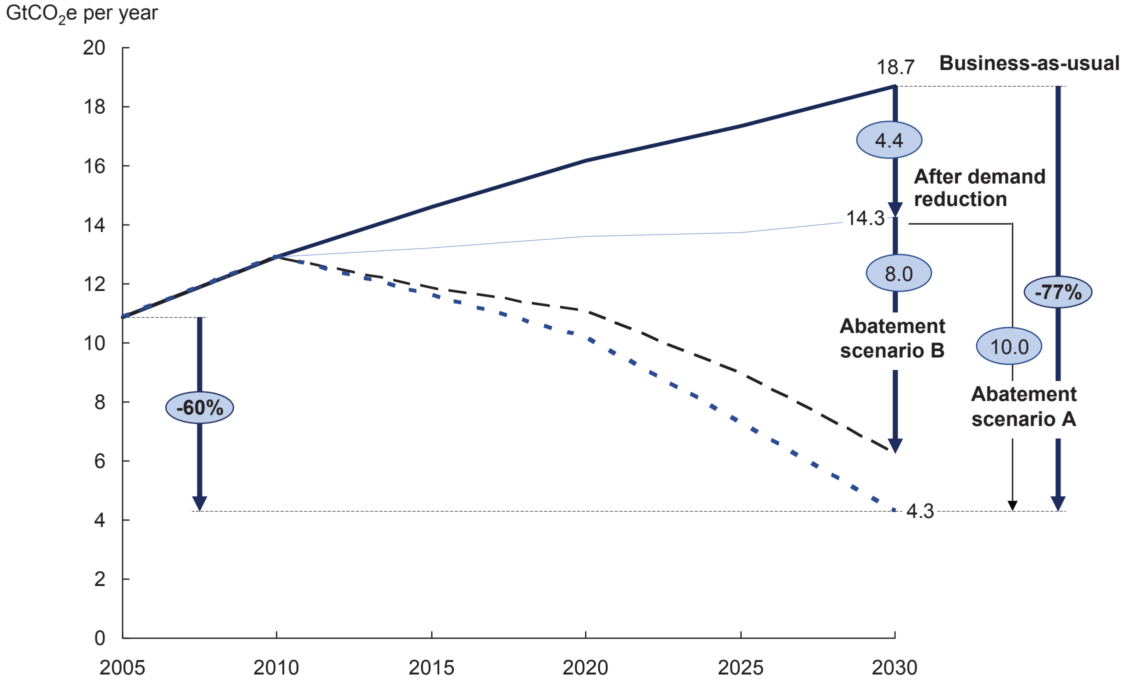
E. **Maximum growth of renewable and nuclear energy.** This scenario assumes that each low-carbon technology is built out to its maximum estimated potential in each geographic market by 2030 (see Appendix IV for the estimates on each technology). The potential per technology depends on its relative cost competitiveness, and on the need for new power generation capacity in each country in each time period up to 2030. This scenario results in a major change in the mix of new capacity built compared to the BAU case and major changes in the overall 2030 power mix. This is the scenario used in the global cost curve, aggregated across all sectors.

F. **50 percent growth of renewable and nuclear energy.** This scenario recognizes that while the growth rates for each low-carbon technology in Scenario A is realistic, the total scale of change for the Power sector under Scenario A is massive and that, even if there were to be aggressive global policy action in support of reducing emissions, it is not unlikely that one or more technologies would fall short of the estimated potential. To illustrate what such challenges could mean for the sector, we have constructed a Scenario B that limits the growth rate of key renewable technologies (wind, solar PV, solar CSP, biomass) and nuclear energy to 50 percent of the potential in Scenario A. Instead, more fossil-fuel-based power generation capacity is built under this scenario, some of it equipped with CCS.

Interestingly, both scenarios result in broadly similar emissions levels and cost levels in 2030. This is because there are so many low-carbon technologies that in a 2030 time horizon look likely to have an abatement cost below our threshold of €60 per $tCO_2e$, and their combined potential outweighs the need for new power generation capacity. In fact, it is in Scenario A the pace at which existing fossil fuel plants need to be replaced that limits the abatement potential. The result is that if one or a few technologies fall short

Exhibit 8.1.1

**Emissions development for the Power sector – Scenarios A (maximum renewables/nuclear) and B (50 percent renewables/nuclear)**




* Economic potential of technical measures

Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

of their potential, other technologies can largely make up for the loss in abatement. For example, the higher number of fossil-fuel plants built under Scenario B would increase the opportunity for CCS by more than 35 percent and largely compensate for the abatement losses from renewable and nuclear energy.

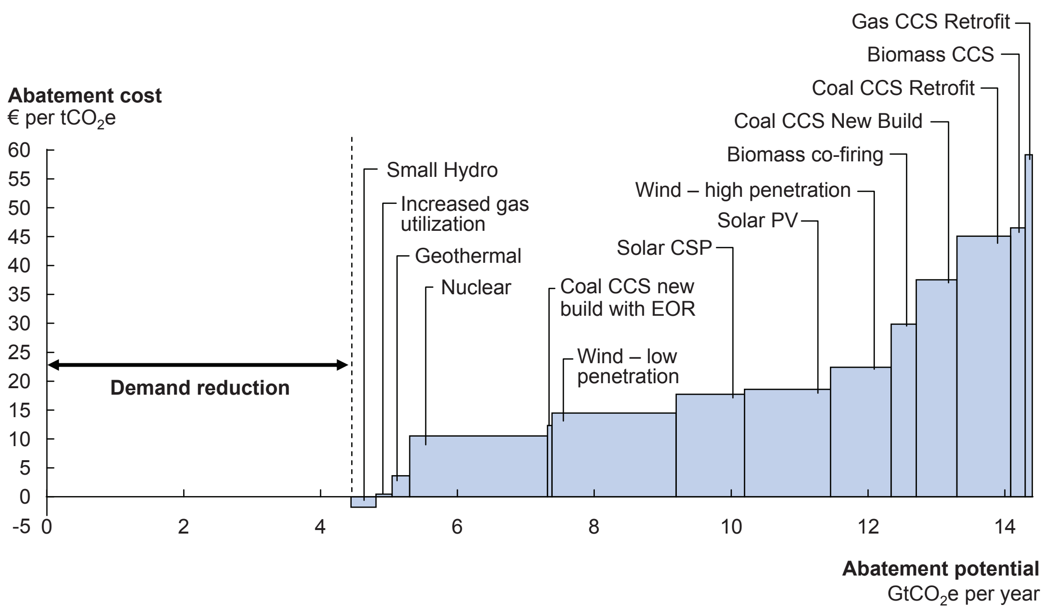
**Scenario A: Maximum growth of renewable and nuclear energy.** With an overall abatement potential of 14.4 $GtCO_2e$ per year in 2030, including demand reductions of 4.4 $GtCO_2e$ per year from other sectors (due to energy efficiency), this scenario results in 2030 emissions that are about 60 percent below the 2005 level. Renewable sources of power form the largest share of the abatement potential, with more than 6 $GtCO_2e$, or about 60 percent of the overall potential within the Power sector. CCS levers combine to produce emissions abatement of around 1.8 $GtCO_2e$ per year, while nuclear energy accounts for roughly 2.0 $GtCO_2e$ per year of the potential. The cost curve for this scenario shows that several low carbon technologies have a similar abatement cost by 2030 (Exhibit 8.1.2). This reflects the high level of uncertainty about which technologies are likely to prove to be “winners.” Geographically, the largest abatement potential in this scenario comes from China, the United States, and India, adding up to over 65 percent of the total potential – slightly more then these countries’ share of emissions, which is about 60 percent. In our modeling, we have taken into account that there are long construction lead-times for power plants, in particular for coal, hydro and nuclear plants. Due to this, the abatement potential that we have modeled in the 2010–2015 period is significantly lower than it would otherwise have been.

In Scenario A, the power-production mix in 2030 is in stark contrast to the BAU case, showing a drastic shift toward cleaner generation methods (Exhibit 8.1.3). Whereas in the BAU case about 70 percent of electricity comes from fossil-fuel plants in 2030, only about 35 percent does so in the Scenario A abatement case. This reduction is mainly driven by the significant replacement of to-be-built fossil fuel plants by renewables and nuclear in high-growth countries such as China. On a global level, renewables (including large hydro) and nuclear energy account for about 65 percent of the power mix. While this may

**Exhibit 8.1.2**

## Global GHG abatement cost curve for the Power sector – Scenario A: Maximum growth of renewables and nuclear energy

Societal perspective; 2030

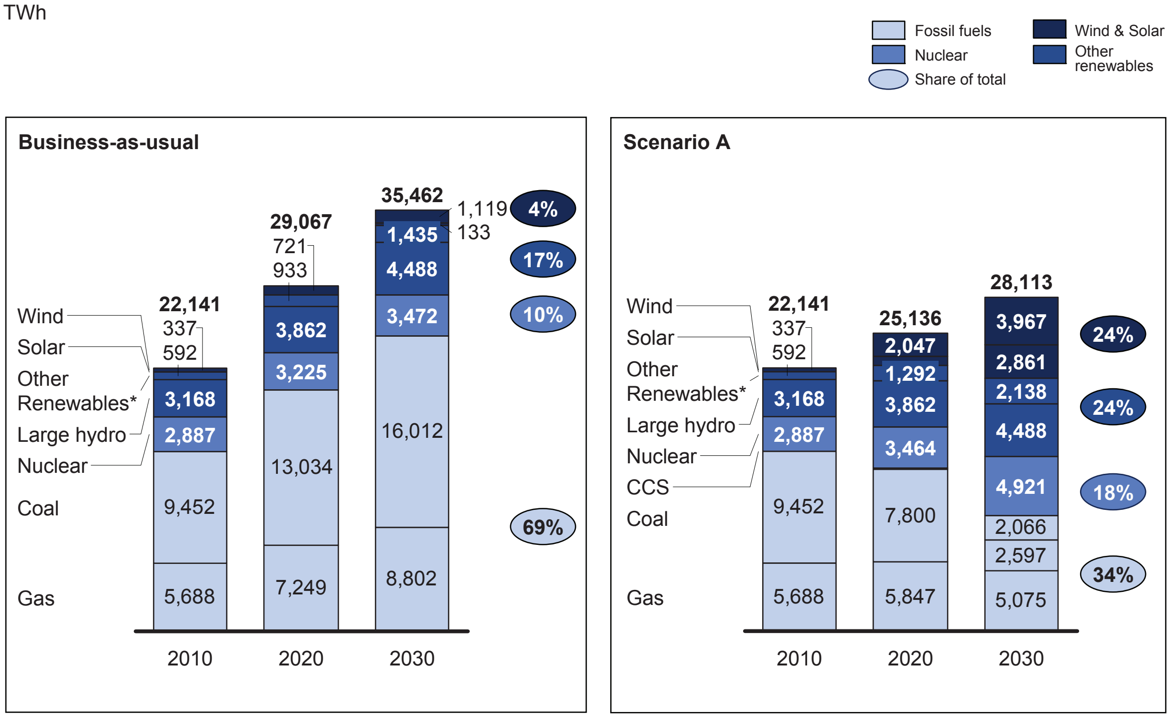



Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

**Exhibit 8.1.3**

## Production mix – Scenario A: Maximum growth of renewables and nuclear energy

TWh




* Small hydro, geothermal and biomass
Source: Global GHG Abatement Cost Curve v2.0

seem a very high proportion, the share of intermittent power sources (i.e., wind and solar PV) has in our model been capped at 20 percent of the power production in any individual country[38]. This 2030 power production mix would make the $CO_2$ intensity of the Power sector decrease from around 600 $tCO_2e$ per GWh in 2005 in the BAU to about 170 $tCO_2e$ per GWh in 2030.

The average abatement cost in this scenario – if all the levers in the Power sector are implemented[39] – is about €20 per $tCO_2e$, and the total investments in power generation – in addition to the BAU investment levels – would be approximately €50 billion per year in 2015, and approximately €150 billion per year in 2030. This makes the Power sector, together with Buildings and Transport, the sectors that see the highest need for additional investment to reach their full abatement potential. The average abatement cost is highly sensitive to the cost of fossil fuels; the higher the cost of fossil fuels, the lower the relative cost of replacing them with low-carbon alternatives. In a high fossil fuel price scenario, which assumes oil at $120 per barrel (€80 per barrel) and other fossil fuel prices changing proportionally[40], the average abatement cost would decrease from €20 to €9 per $tCO_2e$, and vice versa in a low fossil fuel price scenario.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | 20 | 52 | 3 |
| **2020** | 17 | 96 | 1 |
| **2025** | 18 | 147 | -7 |
| **2030** | 20 | 148 | -2 |

Abatement action in the Power sector is also very sensitive to time. Delaying abatement action for ten years, for example, would decrease the abatement potential to 5.2 $GtCO_2e$ per year by 2030, a reduction of almost 50 percent compared to if abatement action would start already in 2010. What is more, this delay would lock in emissions from new-build fossil-fuel plants that would likely last beyond 2050, as the lifetime of a coal plant is often more than 40 years. The delay would also postpone the learning effects of emerging low-carbon technologies and make them more expensive in a 2030 time horizon.

**Scenario B: 50 percent growth of renewable and nuclear energy.** By significantly limiting the growth of renewable energy and nuclear relative to Scenario A – to reflect the huge challenge of the sector to shift around the investment mix so fast – this scenario sees more fossil capacity being built, some of it equipped with CCS technology. The total abatement potential is around 12.4 $GtCO_2e$ per year (including the same demand reduction) in 2030 at an average cost of some €21 per $tCO_2e$. Interestingly, this abatement potential is only 2 $GtCO_2e$ lower than in Scenario, and the average cost is only about €1 per $tCO_2e$ higher. The merit order of the levers on the cost curve remains similar (Exhibit 8.1.4), but the potential of renewable energy and nuclear decrease and, depending on their respective learning rates, they also increase in costs. The loss in abatement potential is partly compensated by an increase in CCS potential of around 0.7 $GtCO_2e$ per year.

In Scenario B, intermittent power sources reach roughly 16 percent of the 2030 power mix, while fossil fuels (including CCS levers) account for nearly half of total power production (Exhibit 8.1.5).

## Implementation challenges

38 Some countries such as Denmark already approach similar levels.

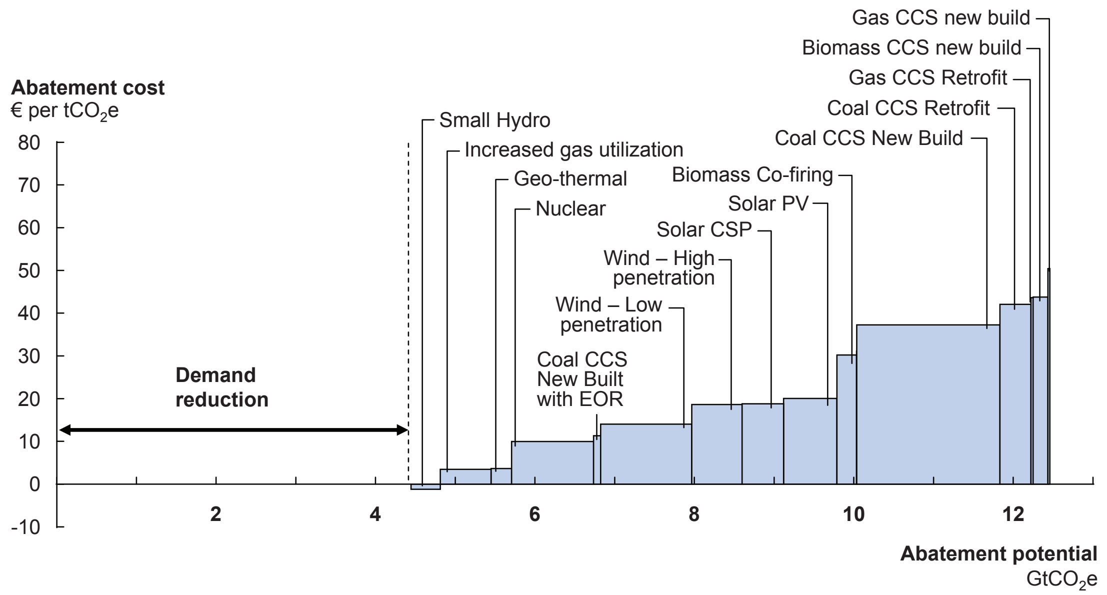
39 Only the cost of abatement levers within the Power sector is included, i.e. the cost of measures in other sectors that reduce electricity consumption is not included in this calculation

40 Our base case fuel price assumptions are taken from the IEA's World Energy Outlook 2007: oil at $60 a barrel (€40 a barrel), gas at €5 per MBTU, and coal at €40 per tonne. In the high price scenario, oil price is at $120 per barrel, gas at €9 per MBTU, and coal at €75 per tonne.

**Exhibit 8.1.4**

## Global GHG abatement cost curve for the Power sector – Scenario B: 50% growth of renewables and nuclear energy

Societal perspective; 2030

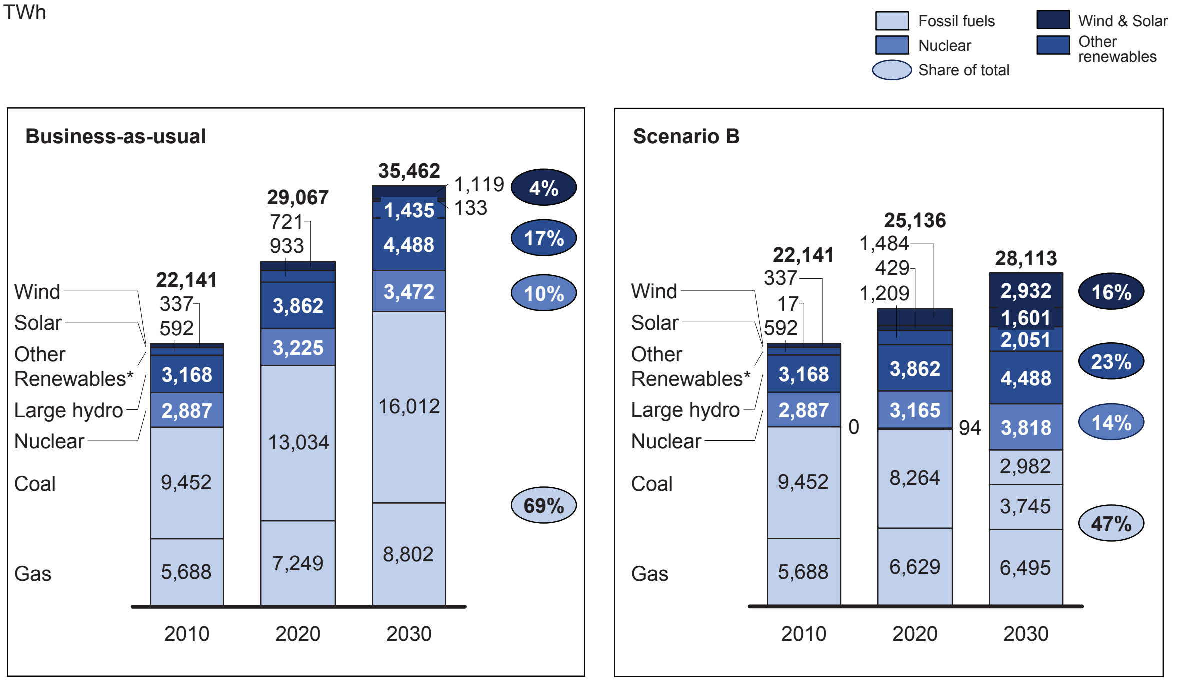



Note: The curve presents an estimate of the potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively, taking into account the supply assumptions of scenario B. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

**Exhibit 8.1.5**

## Production mix – Scenario B: 50% growth of renewables and nuclear energy

TWh




* Small hydro, geothermal and biomass
Source: Global GHG Abatement Cost Curve v2.0

The Power sector has many characteristics that make implementation less challenging than in most other sectors. First, the sector consists of a relatively small number of large companies, which are used to regulation and to taking regulatory incentives into account when prioritizing investments. Second, consumer implications are relatively limited (except for a potentially higher electricity price) and third, compliance is comparatively easy to measure and monitor.

Instead, the biggest implementation challenges seem to be related to technology and cost. Many of the key low-carbon technologies are not cost competitive today today and need to travel down the learning curve. If policy makers want to see utilities investing in them, they should design incentive systems that compensate for the higher cost and make investments in these emerging technologies attractive. There are also regulation-related implementation challenges in many countries: grid regulation often needs to be adapted to allow for integration of the new-generation technologies, permitting processes to build new power plants are often long, and the long-term development of the regulation is often highly uncertain – a problem for a business where assets often have a life time of several decades. Furthermore, utilities will need to learn how to build and maintain these new-generation technologies and how to integrate them in an effective way into existing energy systems.

## 8.2 Petroleum and gas

The Petroleum and Gas sector emits 2.9 $GtCO_2e$ per year, corresponding to 6 percent of total global 2005 $CO_2e$ emissions (including indirect emissions).[41] In the absence of abatement measures, emissions from petroleum and natural gas production, transport, and refining are predicted to grow by one-third to around 3.9 $GtCO_2e$ per year by 2030. Upstream, midstream, and downstream segments each account for a large share of total emissions. A range of abatement options could reduce petroleum and gas emissions in 2030 to a level that is 14 percent below 2005 emissions – much of it at a net benefit to society. The three main abatement categories are process changes and improvements, mainly in non-OECD countries (around 250 $MtCO_2e$ per year); energy-efficiency improvements, mainly in downstream refining (about 350 $MtCO_2e$ per year); and Carbon Capture and Storage (CCS), mainly in downstream refining in OECD countries (approximately 450 $MtCO_2e$ per year). The main implementation obstacles are technological maturity and funding for CCS, the dispersed ownership of assets, misaligned incentives between companies and society, differences in capabilities between oil companies, and a shortage of capital and engineering capacity.

### Business-as-usual emissions

For petroleum, the scope of this study includes production and refining activities. The scope excludes emissions from the sea freight of petroleum, which is covered in the Transportation sector analysis; petrochemicals, covered in the Chemicals sector; distribution, covered in Transportation; and marketing and final consumption that are covered in the Power, Buildings, and Transportation sectors. This analysis also excludes the exploration and development of petroleum as these do not produce material GHG emissions.

For natural gas, the scope of this study includes production, transmission, liquefied natural gas (LNG), and distribution. Emissions from sea freight and trucking of natural gas are covered in the Transportation sector analysis while retailing is covered in both the Power and Buildings sectors.[42] This analysis does not include the exploration and development of natural gas, gas-to-liquids (GTL), and coal-to-liquids (CTL) because their GHG emissions are too small to be material.

41 Indirect emissions are 0.3 $GtCO_2e$ and 0.4 $GtCO_2e$ in 2005 and 2030 respectively.

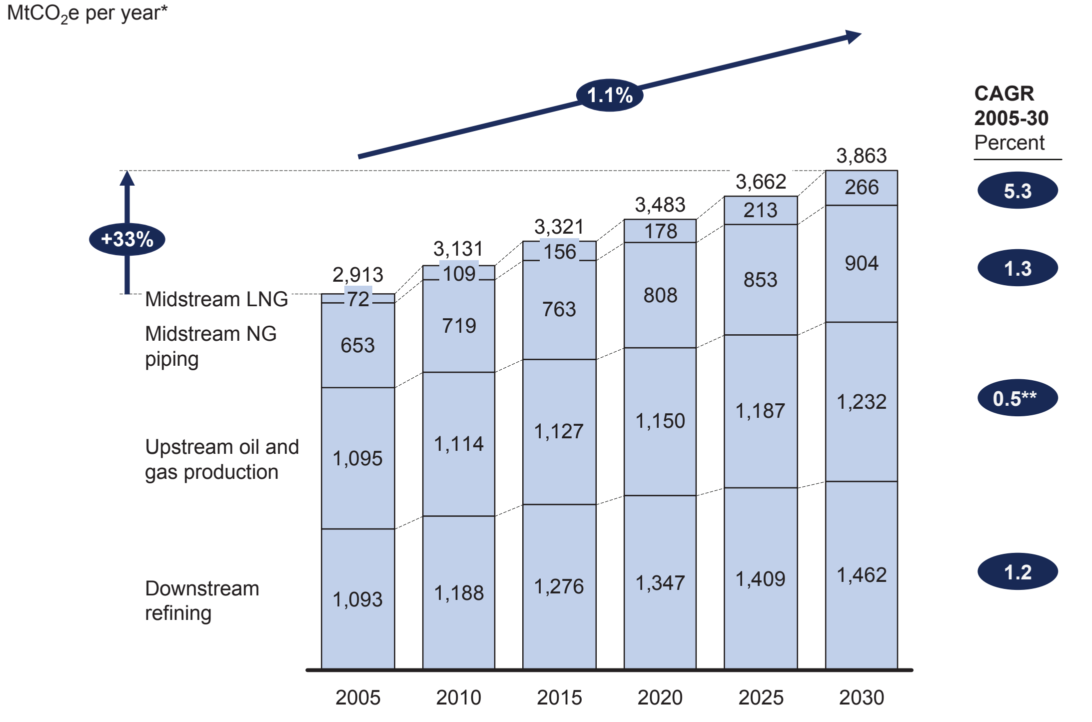
42 LNG boil-off is included in this analysis.

In the absence of abatement measures, emissions in the Petroleum and Gas sector are estimated to grow by 1.1 percent annually through 2030 to reach 3.9 $GtCO_2e$ per year (Exhibit 8.2.1). The BAU case (i.e., without abatement measures) assumes a portfolio shift away from conventionally produced oil; the share of natural gas in global upstream production will grow from 37 percent in 2005 to 41 percent in 2030, and the proportion of non-conventional oil will grow from 1 to 3 percent over the same period.

**Exhibit 8.2.1**

## Business-as-usual emissions in the Petroleum and Gas sector

$MtCO_2e$ per year*




* Including indirect emissions
** Strong Increase in production and processing emissions offset by a strong reduction in flaring emissions
Source: Global GHG Abatement Cost Curve v2.0

Emissions in 2005 from upstream and downstream operations each represented about 38 percent of total sector emissions, with midstream emissions accounting for the other 24 percent. Strong global demand for gas and fuel products between 2005 and 2030 is expected to drive overall growth in $CO_2$ emissions.[43] Demand in all oil and gas segments will be driven by rapid economic development in China, India, the Middle East, and Russia, as well as a shift to gas.

- **Upstream production and processing.** Demand is expected to grow by 47 percent between 2005 and 2030. Moreover, the energy intensity per barrel produced will increase due to a portfolio shift towards more energy-intense gas and non-conventional oil production and a greater need for enhanced oil recovery (EOR) and energy-intense artificial lift because of maturing oil fields.[44] Yet total upstream emissions will increase by only 12 percent, due to a strong anticipated reduction in flaring emissions (a decrease of some 72 percent). This is because of increasing public pressure to reduce flaring and the natural incentive caused by high gas prices. It is to be noted however,

43 Demand for gas in 2005–2030 is forecast to grow at 1.9 percent annually, for conventional oil at 1.2 percent, and for non-conventional oil at 4.7 percent.

44 The ratio of carbon intensity between non-conventional to conventional oil production varies based on the maturity of the fields. Non-conventional is estimated to have 2-5 times higher carbon intensity than conventional.

that there is a great deal of uncertainty about upstream emissions, particularly in respect of their non-$CO_2$ share in a 2030 perspective. For example, the EPA baseline considers that fugitive and venting emissions will grow with increasing oil and gas production, leading to non-$CO_2$ emissions higher than 1.0 $GtCO_2e$ per year by 2030. However, there is evidence that these emissions are already being reduced, as the effectiveness of investments in emissions reductions is high given the high global warming potential of methane. Thus, the BAU case in upstream assumes those fugitive and venting emissions to decrease significantly.

- **Midstream transmission and distribution.** The main emissions in this segment are the result of gas compression for gas transport and methane leakage during the transport and distribution of gas. As a result of a strong increase in total gas demand (60 percent) and a tripling of LNG, total midstream emissions will grow by around 60 percent between 2005 and 2030 in the BAU case. Although LNG is energy-intense on a per-barrel of oil equivalent (BOE) basis, its usage is more efficient than pipeline transport for long distances. LNG emissions during transport are only 10 to 20 percent of the total carbon content of gas.
- **Downstream refining.** Segment emissions are forecast to grow from 1.1 $GtCO_2e$ per year in 2005 to 1.5 $GtCO_2e$ per year in 2030 – a 1.2 percent annual growth rate. The increase in emissions is driven by strong throughput growth as well as increasing process complexity. However, the underlying trend towards more energy-efficient operations is expected to continue in the BAU case, driven by continued high energy costs.

BAU emissions for the overall Petroleum and Gas sector show much stronger growth in developing regions (60 percent in 2005–2030) than in developed regions (17 percent growth), reflecting a relative shift in upstream production and downstream refinery capacity towards those regions.[45] The Middle East, China, and India will account for more than 50 percent of this increase, resulting in a 27 percent share of global emissions from those countries/regions in 2030.

Carbon intensity, which is the ratio of $CO_2$ to energy (i.e., a measure of the "greenness" of different value chains), will vary greatly from region to region by 2030. Canada and Latin America (e.g., Venezuela) will show significantly higher carbon intensities in upstream production due to the relatively large share of non-conventional oil in their production portfolios. Latin America will also have the highest carbon intensity in downstream refining, primarily due to the heavier and more sour crude oil processed in the region.

This reference case is based on data from the International Energy Agency (IEA), United Nations Framework Convention on Climate Change (UNFCCC), the International Association of Oil & Gas Producers, and the Carbon Disclosure Project.

## Potential abatement

Identified abatement levers could reduce 2030 emissions to a level that is some 4 percent below 2005 emissions (14 percent including the effect of reduction in fuel consumption due to abatement in transport sector), abating around 1.1 $GtCO_2e$ per year compared to the BAU case in 2030.[46] This report includes

45 The share of upstream production from the Middle East and Russia will grow from 39 percent in 2005 to 47 percent in 2030. The Middle East and the BRIC nations—Brazil, Russia, India, and China—will increase their share of global downstream refinery capacity from 19 percent in 2005 to 25 percent in 2030.

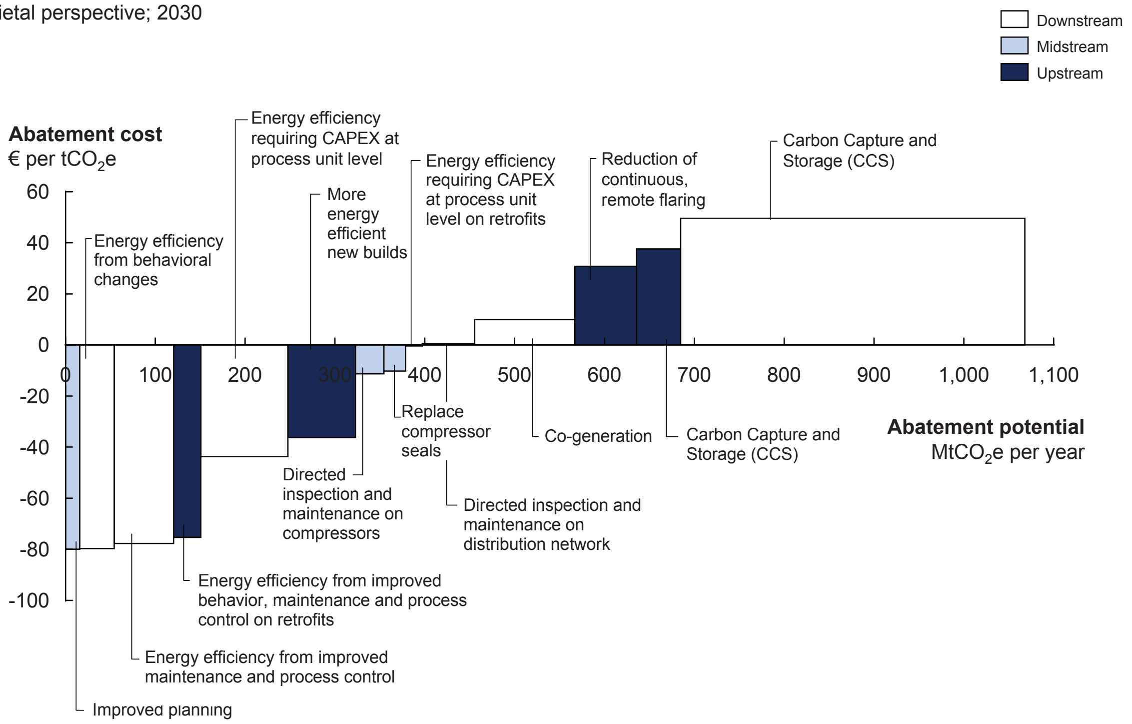
46 In addition to the effect of demand reductions from transport and including the reduction of indirect emissions (which are shown in the power sector as demand reductions).

four main categories of abatement (Exhibit 8.2.2): behavioral and simple process changes; energy-efficiency improvements; CCS; and reduced flaring (only for upstream). These levers encompass the large majority of the abatement potential. Several smaller possible levers exist, including the accelerated replacement of equipment such as compressors, but these have not been included in this analysis.

**Exhibit 8.2.2**

## Global GHG abatement cost curve for Petroleum and Gas sectors

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

**A. "Behavioral" and simple process changes.** Across all three subsectors, improved maintenance and process control can result in significant abatement (of around 240 $MtCO_2e$ per year in 2030) and are net-profit-positive at assumed energy prices:

- In upstream, as well as conservation programs and improved maintenance, measures include reducing fouling build-up in pipes, optimizing well and separator pressures, and optimizing the spinning reserves of rotating equipment. Along with improved process control that reduces suboptimal performance, emissions can be reduced by around 30 $MtCO_2e$ in 2030.[47]
- In midstream, more directed inspection and maintenance of the compressors and distribution networks and better planning can reduce emissions by around 110 $MtCO_2e$ in 2030.
- In downstream, significant abatement (about 100 $MtCO_2e$ in 2030) can come from measures such as energy-awareness programs and optimized process controls in refineries that have not yet implemented large efficiency programs.

**B. Energy-efficiency improvements.** Modifications for energy efficiency could provide around 330 $MtCO_2e$ in emissions reduction, mostly net-profit-positive. These improvements would require capital expenditures at a process or plant level.

47 Due to undesired pressure drops across gas turbine air filters, an undesired turbine washout frequency, and suboptimal well and separator pressures.

- In upstream, a large abatement (about 90 $MtCO_2e$) can be achieved with a program developed to ensure that new-build production facilities are built to best-in-class standards in terms of energy efficiency.
- In midstream, seal replacement can deliver some 20 $MtCO_2e$ per year; other measures related to compressor replacement (e.g., accelerated replacement or electric compression) could provide additional abatement opportunities.
- In downstream, a reduction of around 100 $MtCO_2e$ per year can be achieved through the replacement, upgrade, and addition to equipment that does not alter the process flow of a refinery, e.g., through waste-heat recovery via heat integration and the replacement of boilers, heaters, turbines, and/or motors. Additionally, installing cogeneration units across the industry could provide an additional abatement of about 110 $MtCO_2e$ per year at a low positive cost.

**C. Carbon capture and storage (CCS).** CCS is the single-largest lever for abating oil and gas emissions, with a potential to abate 40 percent (around 430 Mt $CO_2e$) of total sector emissions in 2030, if enough resources – both in terms of capital as well as engineering capacity – are made available. CCS is most applicable for large point sources of $CO_2$ and has therefore the greatest potential in the downstream segment, notably at refineries that are close to storage and have the space and technical flexibility to integrate CCS. For upstream, CCS is considered particularly applicable to in-situ production of non-conventional oil where the energy required is produced in a centralized location.

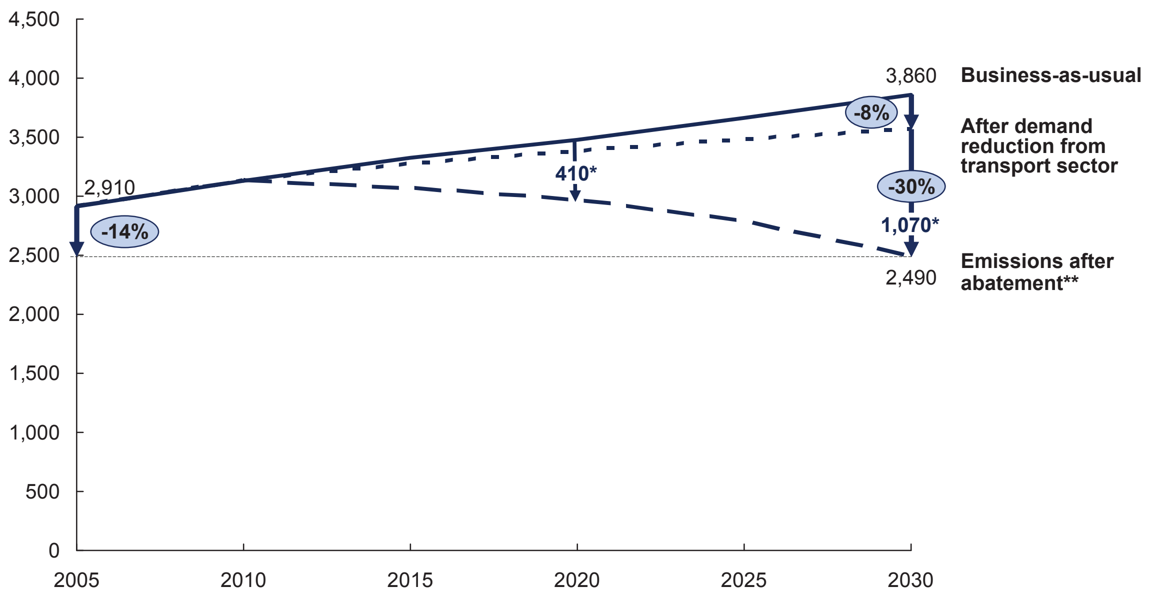
**D. Reduced flaring.** Despite very large anticipated reductions in flaring emissions in the reference case, a further abatement of about 70 Mt $CO_2e$ will remain for flares located in remote regions.

As shown in Exhibit 8.2.3, the potential abatement volume increases over time, due to a gradual implementation of abatement levers in the industry. In particular, the first CCS pilot projects are

**Exhibit 8.2.3**

**Emissions development for the Petroleum and Gas sectors**

$MtCO_2e$ per year




* Reductions shown in the cost curve, thus calculated after demand reduction
** Economic potential of technical measures
Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

forecast to be implemented in 2015 and subsequently rolled out on a larger scale.

At an assumed oil price of $60 per barrel (€ 40 per barrel), the average cost for all emissions abatement levers is expected to be around € 4 per $tCO_2e$ in 2030, much higher than in previous years. Indeed, heavy investments in CCS, cogeneration, and measures to reduce continuous remote flaring counteract the net-profit efficiency measures in those later years. Yet from a societal point of view the abatement measures would largely pay for themselves. The fact remains, however, that for individual companies, some of the more expensive abatement measures might not be attractive from a financial perspective.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | -24 | 6 | -4 |
| **2020** | -16 | 11 | -10 |
| **2025** | -5 | 14 | -13 |
| **2030** | 4 | 18 | -12 |

Most identified abatement levers require high upfront capital investments, followed by savings in operating expenditures due to reduced energy requirements. Investment requirements for all levers in 2030 would represent 2 percent of the total investment expected in the industry.

**Geographical differences.** Geographic regions around the world have comparable abatement potential, with North America (16 percent of total abatement), Eastern Europe including Russia (16 percent), and the Middle East (13 percent) having slightly larger shares of the global total than other regions.

The main drivers for emissions abatement differ significantly by region. CCS will be the main abatement lever in Western Europe (61 percent of the abatement potential through 2030), North America (56 percent), Latin America (55 percent), and OECD Pacific (59 percent). Broad energy-efficiency programs and cogeneration are the largest levers in China (62 percent of potential), the Middle East (62 percent), India (61 percent), and the rest of developing Asia (52 percent). In Africa, reduced flaring emissions will be the largest lever (30 percent of abatement potential). In Eastern Europe and Russia, reduced emissions from the gas-pipeline network will have the greatest abatement potential (33 percent).

## Implementation challenges

Although this analysis includes a realistic technical implementation schedule for each abatement lever, certain obstacles can prevent companies and regulators from implementing these measures. Significant barriers exist both at an internal company level and at an external or regulatory level.

Internally, petroleum and gas companies face implementation challenges because of a lack of awareness, a scarcity of resources, and relatively high financial hurdle rates:

- For large companies, building increased awareness of the importance of energy conservation and $CO_2$ emissions reduction takes time and continued reinforcement. Conversations about energy conservation must become part of regular management systems, and high-level management attention is required for this focus to remain effective. Recent high energy prices will help in this respect but behavioral changes are always gradual.

- Monitoring of $CO_2$ emissions and the impact of the various measures is essential for the effective implementation of reduction programs. This is a challenge for all companies but especially for the upstream and midstream operations of large oil companies as they tend to have internationally dispersed operations in remote regions.
- With high energy-demand growth, resources are scarce within oil and gas companies. In many cases, companies will have to choose between allocating scarce capital and engineering capacity to their core business (such as finding more resources) or energy-conservation programs.
- The current knowledge and skills required to implement energy-efficiency programs differ significantly between companies. Building these skills or transferring them between companies will take time.
- Finally, many energy-efficiency measures may not pass companies' internal hurdle rates. For some opportunities, companies could consider lower hurdle rates, reflecting the different risk profile of some cost-saving opportunities, but in many cases additional guidelines and targets will be required to achieve higher reductions.

Differences between companies can be large, and the regulatory and public environment in which a company operates can have a substantial influence on which obstacles prove most significant and how a business responds.

External obstacles vary greatly between countries. As noted, some developing countries have insufficient oil and gas infrastructure, making implementation of abatement measures difficult or very costly. Moreover, fuel subsidies or the existence of stranded resources or export bottlenecks reduce the upside of adopting energy-savings measures. Stranded resources and export bottlenecks both imply too much fuel and/or a low local fuel price, both of which encourage the wasteful use of energy.

Moreover, the cost curve shows that CCS can provide the single-biggest reduction in $CO_2e$ emissions for the Petroleum and Gas sector. However, given its early stage of development, much uncertainty on the potential of this technology still exists and multiple obstacles need to be overcome. For downstream, CCS still needs to enter the pilot phase and although individual CCS technologies are proven independently, they have not been applied in an integrated manner and on a large scale in a refining environment. Moreover, CCS requires significant funding as the initial plants are more expensive and storage availability will largely depend on the region. Finally, a clear regulatory framework will be required for the transport and storage of the gases, which does not yet exist in most regions.

In summary, abatement options for the Petroleum and Gas sector are well-known and feasible in the medium term. If these abatement levers are implemented, the Petroleum and Gas sector could maintain constant or even declining total emissions despite significant demand growth. However, execution of the measures will require the involvement of all major companies and governments.

## 8.3 Cement

The Cement sector represented emissions of 1.8 $GtCO_2e$ per year in 2005, which is approximately 4 percent of total global emissions and about 11 percent of worldwide industrial emissions.[48] China is the largest producer of cement and thus its related emissions, producing around 45 percent of the worldwide total in 2005. In the absence of abatement measures, cement emissions are projected to grow 3 percent annually through 2030, driven mainly by economic growth, infrastructure development, and urbanization in developing countries. Identified abatement levers would cut emissions by 25 percent relative to this BAU case. Most of the abatement potential is achievable using conventional technologies. The majority of abatement potential would be net-profit-positive to society. A challenge to a reduction of cement emissions is that we do not anticipate that the breakthrough technology of carbon capture and storage will be available before 2020 at the earliest.

Cement is the essential ingredient in concrete, the main building material for buildings and infrastructure. Concrete is second only to water as the most consumed substance on earth, with approximately 20 billion tonnes used annually by society. Cement is therefore important to economic growth and development and is a major industry in most regions of the world. Total global cement production in 2005 was approximately 2,350 megatonnes. Cement is predominantly a regional industry, although there is some international trade. Driven by its rapid economic growth and urbanization, China is by far the biggest country in terms of cement production and related $CO_2$ emissions, alone accounting for some 45 percent of global production in 2005. No other region produces more than 10 percent of the global total. An average cement plant typically emits around 1 $MtCO_2e$ per annum, and sources of emissions in the industry are relatively concentrated;

The main constituent of cement is clinker. This intermediate product is produced in a high-temperature process for the calcination and mineralization of limestone. Ordinary Portland cement is composed of about 95 percent clinker and about 5 percent gypsum, ground to a fine dry powder. Depending on the application, product qualities, and product and building standards, clinker can be substituted to different extents by other mineral components, including granulated slag from the steel industry, fly ash from coal-fired power plants, and natural volcanic materials, producing composite cements.

48 This category includes indirect emissions from electricity consumption of 0.2 $GtCO_2e$ per year.

There are three categories of $CO_2$ emissions from cement production:

- **Process emissions.** Direct emissions from the calcination process constituted some 54 percent of global cement $CO_2$ emissions in 2005.
- **Fuel-combustion emissions.** These direct emissions accounted for around 34 percent[49] of the total in 2005.[50]
- **Indirect emissions.** Related to electricity consumption, these emissions made up around 12 percent of the total in 2005.[51]

The clinker production process is the most $CO_2$-intensive aspect of the Cement industry, accounting for all process emissions and more than 80 percent of the emissions from fuel combustion. There are no material emissions of other GHGs by the cement industry.

The cement sector emitted 1.8 $GtCO_2e$ per year in 2005, which is 4 percent of total global GHG emissions. Emissions intensity and clinker content in cement differ substantially between regions, ranging from around 0.63 $tCO_2e$ per tonne of cement in 2005 in Germany to some 0.81 $tCO_2e$ per tonne in North America and even approximately 0.90 $tCO_2e$ per tonne in Russia. The global average for carbon intensity from cement production in 2005 was 0.79 $tCO_2e$ per tonne.

## Business-as-usual emissions

In the BAU case, the Cement industry's absolute emissions will increase by 111 percent from 2005 to 2030 – i.e., 3.0 percent annually – to 3.9 $GtCO_2e$ per year. Global emissions will increase at a lower annual rate than global production of cement (3.2 percent annual growth in 2005–2030), due to a more efficient production base, as the least fuel-efficient cement kilns are retired and replaced with best-available technology (BAT).[52] In China, authorities have announced the retirement of all shaft kilns before 2020.[53] The reference case assumes this significant capital investment to update worldwide cement-industry assets from a BAT ratio of around 54 percent in 2005 to 97.5 percent in 2030. We assume that this asset-renewal process will harvest fully the technical potential to improve energy efficiency in clinker production. This major investment solely impacts fuel-combustion emissions but leaves process emissions unaffected. Carbon intensity will improve by 4 percent globally from 2005 to 2030 in the BAU case.

BAU growth in emissions is anticipated to be highest in the BRIC (Brazil, Russia, India, and China) economies and the rest of developing Asia and Africa, driven by rapid economic growth, infrastructure development, and urbanization. For example, emissions growth in India is projected at 8 percent annually, driven by increasing cement production. Growth in emissions is expected to be much slower in the developed world.

49 Accounting for $CO_2e$ from biomass as climate-neutral and accounting for the $CO_2e$ emission savings for society resulting from the recovery of waste as a source of energy.

50 Emissions related to transportation of cement materials and fuels are treated in the Transportation-sector analysis.

51 Reductions in indirect emissions are accounted for only if saved within the Cement sector; improvements in the Power sector are accounted for in that sector.

52 BAT for cement is a process using dry kilns with both pre-heater and pre-calciner.

53 Increased fuel energy efficiency due to retirement of the least-efficient kilns has been included in the BAU case.

The 2005 baseline and reference case emissions development are based on data from multiple sources, including the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC), the Cement Sustainability Initiative (CSI), and the European Cement Research Academy (ECRA), as well as scenario analyses by the authors. Reference case emissions calculations depend on cement demand and production and average clinker ratio forecasts by region.

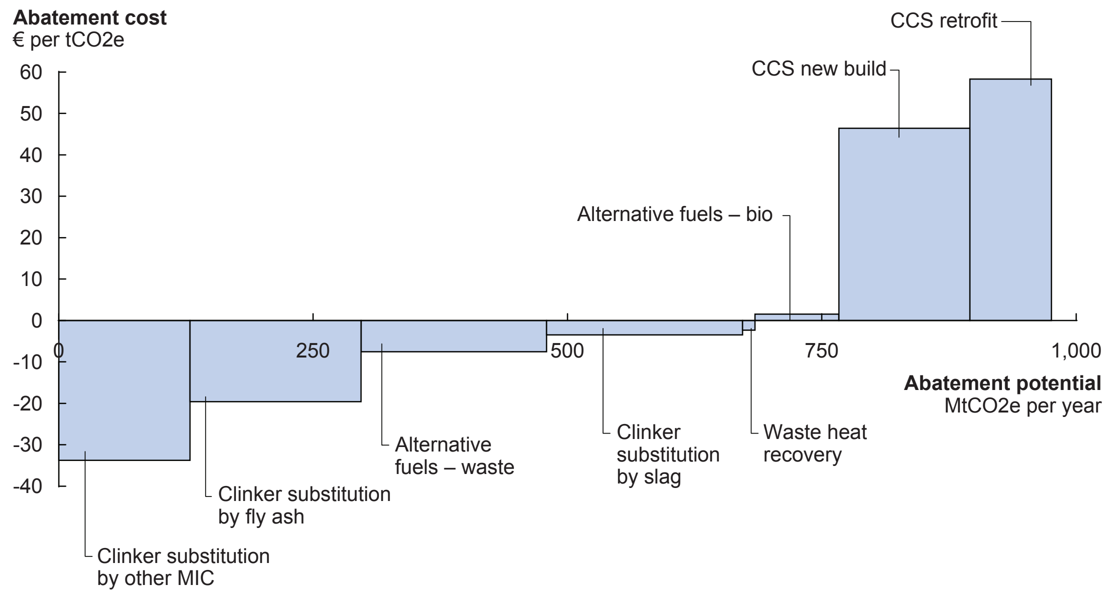
## Potential abatement

We have identified eight abatement levers in the Cement sector, which we can aggregate into four groups (Exhibit 8.3.1):

**Exhibit 8.3.1**

### Global GHG abatement cost curve for the Cement sector

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

A. **Increased substitution of clinker by mineral components in cement (50 percent of abatement potential, around 490 $MtCO_2e$ per year).** Substituting clinker with granulated blast-furnace slag, fly ash, and other mineral components lowers all types of emissions from clinker production, including process, fuel combustion, and indirect emissions.[54] Compared with the clinker share of 82 percent in 2030 in the BAU case, the abatement case clinker share is estimated at 70 percent globally. The increased clinker substitution takes into account the regional availability of the mineral components, linked to actions in the steel and power sectors.[55] In the abatement scenario, all blast-furnace slag from the steel industry will be granulated and sufficient fly ash from coal-fired power stations will be dry-discharged.

54 The only exception is clinker substitution with slag for which power consumption and consequently indirect emissions go up.

55 We assume coal production that is higher than 2005 levels. In the event that the Power sector succeeds in decreasing coal consumption significantly or keeping it at the 2005 level, the Cement sector abatement potential for fly-ash substitution for clinker may need to be revised

We account for the different clinker substitution potential of the mineral components (i.e., the K-factor of slag, fly ash, and other MIC).

B. **Increased share of alternative fuels in the fuel mix (27 percent of abatement potential, around 260 Mt$CO_2$e per year).** Substituting conventional fossil fuels by alternative fuels, such as municipal and industrial waste and biomass, in the cement kiln reduces average direct fuel-combustion emissions of the clinker-making process. The estimated abatement potential assumes that: (a) $CO_2$ from biomass is climate-neutral; (b) the real reductions of $CO_2$ emissions at the alternative waste-disposal operations are attributed to the Cement sector;[56] and (c) sufficient waste and biomass is available locally to replace fossil fuels at an energy substitution rate of 33 percent in total (25 percent from waste and 8 percent from biomass), compared with less than 5 percent globally in the BAU case.

C. **Carbon capture and storage (CCS) (22 percent of abatement potential, around 210 Mt$CO_2$e per year in net terms or around 290 Mt$CO_2$e per year at the source).** CCS is the capture of $CO_2$ from a point source such as a cement kiln and its subsequent sequestration through methods such as injection into subterranean formations for permanent storage. CCS can be added to new cement-production facilities or retrofitted to existing plants. CCS technology is in an early stage of development and CCS transport infrastructure has yet to build out. CCS is assumed to be available starting in 2021 for newly built plants and from 2026 for retrofits of existing capacity. The total global share of production capacity equipped with CCS in 2030 corresponds to some 10 percent of total $CO_2$ production capacity.[57]

D. **Waste-heat recovery (1 percent of abatement potential, around 12 Mt$CO_2$e per year).** Usage of excess heat from the clinker burning process for electricity generation reduces electricity consumption from the power grid by 15 kWh/t clinker on average and thus lowers indirect emissions.

E. **Energy efficiency improvement in clinker kilns.** This abatement lever is exhausted in the BAU case through clinker-asset renewal; no additional energy-efficiency improvement potential is considered in the abatement case. The capital investments related to asset-renewal programs toward BAT contribute about 210 Mt$CO_2$e of abatement. Therefore, clinker renewal is an important abatement lever to be implemented. Additional energy-efficiency measures for existing and new plants seem possible beyond clinker-asset renewal, but we have not analyzed this due to the fact that we anticipate that the additional potential is small.

The identified abatement measures for the Cement sector, including CCS, would eliminate 1.0 Gt$CO_2$e per year by 2030, lowering sector emissions to 2.9 Gt$CO_2$e per year worldwide – a 25 percent reduction from the BAU case. The abatement case results in total absolute emissions in 2030 that are 58 percent higher than in 2005 (relative to 120 percent growth in cement volume).[58] Without CCS, cement-industry $CO_2$ emissions will increase 70 percent above the 2005 baseline. The potential abatement volume increases over time due to an increasing implementation rate of abatement measures. With all abatement measures in place by 2030, cement emission levels would almost be stabilized at 2010 levels (Exhibit 8.3.2).

Almost 80 percent of the abatement potential in 2030 is based on conventional technologies such as clinker substitution and alternative fuels, but excluding CCS.

56 In the abatement case, the fossil waste would be used by the cement industry. In the BAU case, it would be incinerated in waste-incineration plants for electric-power production.

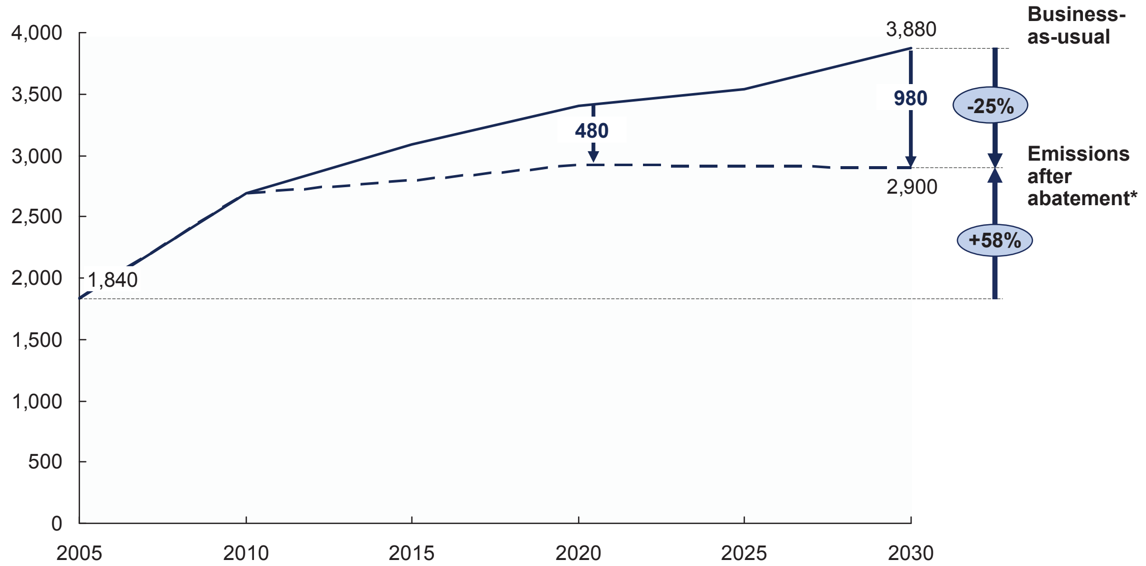
57 Direct emissions to be captured are about 290 Mt$CO_2$e per year; assuming approximately 85 percent capacity utilization would require some 340 Mt$CO_2$e per year of installed capture capacity.

58 The direct emissions (process and fuel combustion) in the abatement case are 41 percent higher and indirect emissions from electricity are 101 percent higher than in 2005, due to increased electricity needs for CCS processes.

**Exhibit 8.3.2**

## Emissions development for the Cement sector

$MtCO_2e$ per year




* Economic potential of technical measures
Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

The average $CO_2e$ productivity of the Cement sector increases significantly in the abatement case. The $CO_2e$ per tonne of cement decreases from an average of 756 kg $CO_2e$ per tonne in the 2030 BAU case to an average of 566 kg $CO_2e$ per tonne in the 2030 abatement case, equaling a decrease of more than one-quarter compared with 2005 levels (Exhibit 8.3.3). When accounting solely for direct emissions (fuel combustion and process), the carbon intensity decreases from 680 kg $CO_2e$ to 490 kg $CO_2e$ per tonne of cement.

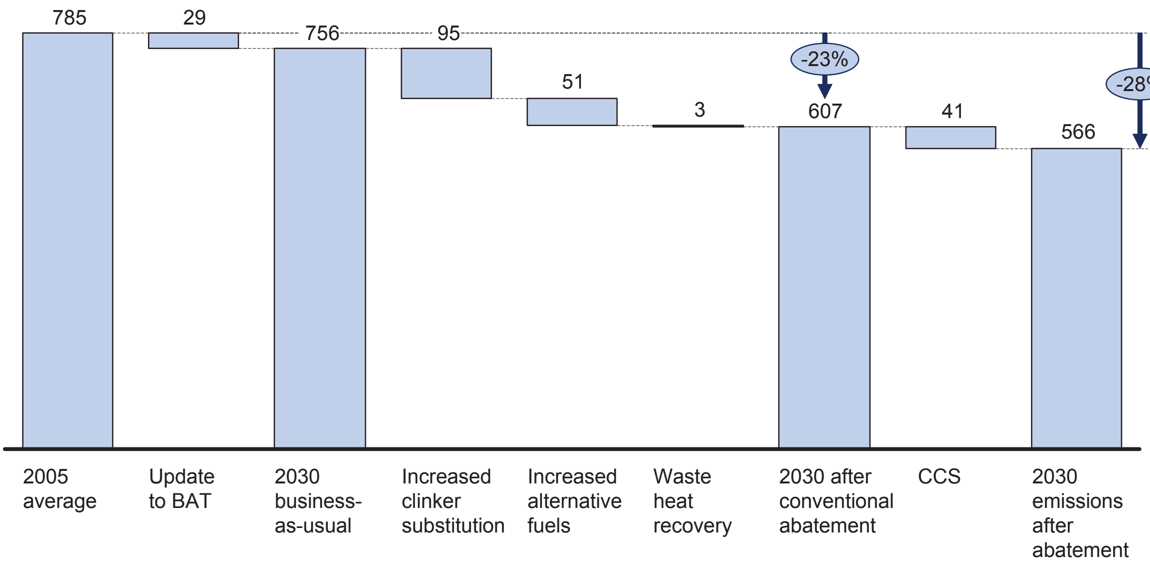
The average cost to society for all abatement measures is negative – i.e., society secures a saving. This is because an extensive substitution of clinker will decrease, to some extent, the need for new builds of clinker-production capacity. Furthermore, the increasing use of waste as a fuel will cut the cost to society of disposing of its domestic and industrial waste. The average cost of abatement will rise starting after 2020 as cost-positive CCS systems become part of the total abatement. All levers based on conventional technology (i.e., excluding CCS) are net-profit-positive or neutral in terms of cost to society and have a negative cash flow. CCS will require capital investments.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | -15 | -9 | -2 |
| **2020** | -14 | -5 | -4 |
| **2025** | -11 | -1 | -5 |
| **2030** | 1 | 6 | -2 |

Exhibit 8.3.3

## Cement $CO_2e$ intensity development by abatement lever group

Kg $CO_2e$ per tonne cement; Global average




Source: Global GHG Abatement Cost Curve v2.0

Capital expenditures in the cement industry are driven by the reduced build-out of clinker production capacity (i.e., the difference between investments for clinker-production assets and investments for using fly ash and slag, leading to negative values to society), increased investment related to increased usage of waste and biomass alternative fuels, higher investment for fly-ash dry discharging and slag granulation and grinding, and CCS capacity build-out after 2020. Operating expenditures in cement are driven by material and transport costs for clinker replacement and additional grinding costs related to grinding slag, fuel costs (especially for alternative fuel levers), and electricity costs.

Not all abatement measures will be equally implemented across regions since implementation relies on feasibility and availability. We find the largest abatement potential in regions with a high clinker share in the reference case and a greater potential availability of substitutes. Approximately 37 percent of the total global abatement potential is found in China (whereas cement production in China accounts for 50 percent of global production), more than 22 percent in India, and more than 10 percent in the rest of developing Asia.

## Implementation challenges

Several conditions are required for the cement emissions abatement levers to succeed:

- **Policies and regulations.** Cement product standards and building codes need to be revised so that these focus on product performance rather than composition to enable the increased usage of composite cements. Policies should allow the exhaustion of waste coprocessing in cement before other solutions such as incineration and landfilling are considered.
- **Availability of materials.** For blast-furnace slag to be substituted for clinker, slag must be made available at a higher granulation rate than is currently the case in the steel industry. The abatement case for the cement sector assumes 100 percent granulation at high quality of all blast-furnace slag from blast-furnace steel production. For fly ash to be substituted for clinker, it must be made available at a higher usable share than is currently available from the Power sector. We base the abatement potential for 2030 on usage of approximately 600 Mt of high-quality fly ash globally. For waste to be used as kiln fuel at the projected abatement-scenario level, waste collection and pre-treatment must provide 25 percent of the global fuel-energy demand of the cement industry. Biomass availability for 8 percent alternative fuel usage also needs to be ensured, given likely competition between sectors. We have taken account of the total biomass availability in all sectors in this study. Overall, capturing the abatement potential in the cement sector depends on supportive actions in other sectors.
- **Avoid carbon leakage.** Asymmetric regulations in certain regions of the world while such regulations remain absent elsewhere could have a counterproductive effect on Cement sector emissions, if this meant that producers shifted production capacity or simply built new capacity farther from target markets due to lower production costs at the expense of higher transport costs. Additional emissions from shipping farther distances would be generated.
- **Technology and infrastructure.** CCS technology is in an early phase of development and must be tested for rollout in the cement industry by 2020. CCS transport infrastructure (pipelines and storage capacity) must be built out in parallel.
- **Sustainable construction.** Suitable policies and practices are critical to achieving further indirect reduction of emissions, including sustainable-construction designs, building codes, and eco-efficient building materials that would allow considerably higher energy efficiency in buildings and infrastructure.

To harvest the full abatement potential described in this report, we assume that all conditions are perfectly aligned and all obstacles are removed. The full potential that we have described is plausible despite all the implementation challenges. It is notable that, in 2006, the cement industry's fifth percentile of best-performing producers had already achieved the emissions intensity of the 2030 abatement scenario and there is every opportunity for all producers to perform according to 2006 BAT in 2030. CCS, if proven viable, will account for the rest of the emissions abatement.

## 8.4 Iron and Steel

The Iron and Steel sector accounts for 2.6 $GtCO_2e$ per year, about 6 percent of total global emissions and about 16 percent of worldwide industrial emissions in 2005. Of this total, 2.1 $GtCO_2e$ per year comes from direct emissions from iron and steel production and 0.5 $GtCO_2e$ per year relates to power consumption. Without the adoption of abatement measures, global emissions from the Iron and Steel sector are projected to grow by 3.2 percent annually, increasing emissions to 5.6 $GtCO_2e$ per year by 2030 primarily as a result of increased production. As the largest producer of iron and steel, China will represent 55 percent of global sector emissions in 2030. With the implementation of identified abatement levers, emission levels can be stabilized at the 2010 level, abating 1.5 $GtCO_2e$ per year (27 percent) compared to the 2030 BAU case. The major abatement levers are improving energy efficiency (the single-largest lever) and Carbon Capture and Storage (CCS) if this technology becomes available.

Iron and Steel is an important industrial sector and a key component of many other industries. The industry is highly fragmented, with the top 10 companies accounting for only 25 percent of total production. As in many other arenas, China is the biggest producer currently; its share is expected to grow from 31 to 44 percent of global production by 2030 (followed by India, Western Europe, and Russia with 15, 8, and 4 percent shares respectively). Iron and steel industry production is anticipated to more than double by 2030, primarily due to rapid economic growth and urbanization in the developing world. But the differences between regions will be stark. While China is forecast to account for 179 percent of emissions growth through 2030, the United States, Italy, Germany, and France are all expected to see declines in their share of emissions by 2030.

Two iron and steel production technologies are widely used: blast furnace/basic oxygen furnace (BF/BOF, the “integrated” route comprised of blast furnace and basic oxygen furnace), and electric arc furnace (EAF). In the BF/BOF process, iron ore is reduced in the blast furnace by the use of coke and pulverized coal injection (PCI) to form hot metal, which is then treated in a basic-oxygen furnace to remove impurities with oxygen and produce steel. An EAF uses primarily scrap metal that is melted by the energy produced by very high-current electricity. As an alternative to scrap metal, Direct Reduced Iron (DRI), produced with coal or gas) is used increasingly in the EAF process. Open hearth furnace (OHF) is a third, older steel-making technology still in use in the developing world (mainly in Russia and former Soviet states) that is expected to be discontinued over the next decade.

There are two forms of carbon emissions from iron and steel production:

- **Process and fuel-combustion emissions.** These direct emissions, primarily from the BF/BOF process, constituted 84 percent of total iron and steel GHG emissions in 2005.
- **Indirect emissions.** Mainly related to electricity consumption in the EAF process, these emissions make up 16 percent of the total.

The integrated BF/BOF process is the most $CO_2$e-intensive process, emitting around 1.6–2.8 t$CO_2$e per tonne of steel (excluding coke/sinter-making and after-treatment), compared with about 0.6–1.8 t$CO_2$e per tonne of steel for EAF steel-making, excluding after-treatment; (EAF emissions depend heavily on how the electricity is produced). The Iron and Steel sector emitted a total of 2.6 Gt$CO_2$e annually in 2005.

## Business-as-usual emissions

Without abatement measures, global emissions from the Iron and Steel sector are forecast to grow by 3.2 percent annually, reaching 5.6 Gt$CO_2$e per year in 2030 – a 118 percent increase over 2005 emissions. Global production of iron and steel is expected to grow at a slightly higher rate than emissions by 3.4 percent annually between 2005 and 2030, from around 1,100 million tonnes to some 2,550 million tonnes. China will account for 55 percent of the growth. The emissions anticipated in the BAU case will grow strongly in Asia but decline in the United States and Western Europe, due to demand and shifts in production technology.

The 0.2 percent difference between industry annual growth and emissions growth is due to ongoing industrial energy-efficiency programs. The historic trend of 1 percent annual improvements in average global emissions intensity is unlikely to continue as future energy-efficiency programs will produce lower returns as absolute performance gets better and as the improvement potential of new greenfield assets is more limited than that of more dated assets. Another factor is the growing rate of iron and steel production in Russia, former Soviet states, and Asia, where carbon intensities are higher than in the Western hemisphere. We assume that net-profit-positive energy-efficiency measures are captured in the BAU case, given high competitive pressure in the industry.

The higher level of emissions in developing countries is caused by a combination of higher energy intensities due to less focus on energy efficiency historically, and higher carbon intensity per steel unit due to the more extensive use of low-quality materials (iron ore and scrap) in steel production as well as in direct fuel.

A shift is expected to take place from BF/BOF technology to EAF technology in the BAU case – from EAF share of 32 percent in 2005 up to an EAF share of 38 percent in 2030. However, this potential is limited by the available supply of scrap, the raw material used in EAF steel production. Less mature technologies such as CCS and coke substitution in the BOF process are not included in the BAU case.

We base the BAU case on regional production data and forecasts from the McKinsey Basic Materials Institute. Baseline emissions data were taken from sinter- and coke-making (for the BF/BOF process), steel-making (for BF/BOF, EAF, and OHF), and the after-treatment process, which comprises the heating and rolling of the steel.

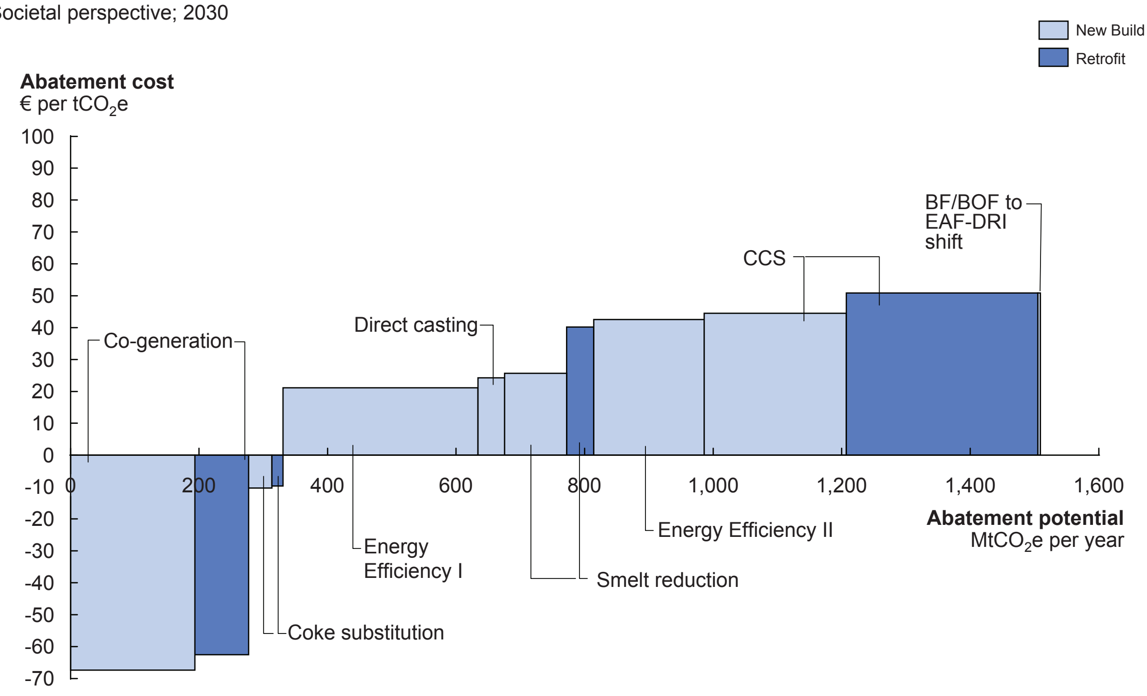
## Potential abatement

We have identified a total of eight abatement levers for the Iron and Steel sector. If all abatement levers were to be implemented by 2030, emissions would be reduced by 27 percent, or 1.5 $GtCO_2e$ per year, compared to the BAU case. We can divide these levers into four groups (Exhibit 8.4.1):

**Exhibit 8.4.1**

### Global GHG abatement cost curve for the Iron and Steel sector

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

**A. Energy-efficiency measures (62 percent of abatement potential, 930 $MtCo_2e$ per year).** This first category accounts for 32 percent of the total abatement potential (about 480 $MtCO_2e$ per year), achieveable through integrated energy efficiency measures. We group this category into two bundles that have different costs. The cheaper bundle includes, for example, continuous improvement measures, preventative and better planned maintenance, the insulation of furnaces, improved process flows, sinter plant heat recovery, coal-moisture control, and pulverized coal injection. The other, more expensive, bundle includes, for example, oxygen injection into EAF, scrap preheating, flue-gas monitoring systems, improved recuperative burners, and BOF gas recycling.

In addition, technological changes (some limited by available technology, commercial constraints, product specification constraints) like Direct casting, integrating casting and after treatment process steps into one step, can lead to some 3 percent of total abatement potential (about 40 $MtCO_2e$ per year). We assume an average energy saving of 18 percent in after-treatment energy consumption for new-build plants. Cogeneration could create a further 18 percent of the total abatement potential (around 270 $MtCO_2e$ per year), assuming that BF/BOF steel mills can be self sufficient with regard to electricity by implementing this lever. Cogeneration is a method in which gas from the BF/BOF process is recovered, cleaned, and used for power generation at the steel mill. Smelt reduction, where ore reduction and steel production are combined in the same equipment, can contribute around a further 9 percent (about 140 $MtCO_2e$ per year) of abatement. In total, these energy-efficiency measures, combined with the efficiency effects in the BAU case can lead to a total energy-consumption improvement of 15 to 20 percent, with regional variations within this range.

**B. Fuel shift.** Substituting coke used in BF/BOF furnaces with fuel based on biomass (charcoal) can lead to 3.5 percent of abatement potential, some 55 $MtCO_2e$.

**C. Process change.** Switching more aggressively from BF/BOF to EAF compared with the BAU case could yield 0.3 percent, or around 4 $MtCO_2e$ per year, of abatement potential. Since EAF technology cannot use iron ore per se as a raw material, and the supply of scrap metal used tends to be limited (as steel is recycled after an average 10 to 20 years depending on the application), emissions reductions are made when switching to EAF-DRI. In this case, natural gas is used to reduce iron ore, producing direct reduced iron (DRI) that can substitute for scrap as the raw material in EAF furnaces. The use of this methodology is a more costly production alternative in most regions because of the use of gas as fuel. For this reason, the BAU case assumes that this shift does not take place. (Some regions such as the Middle East are structurally advantaged in this respect and can use the gas for many uses. Other regions, such as Siberia, Kazakhstan, Iran, and Iraq, have iron ore and stranded gas with limited alternative-usage options and could therefore be interested in developing this methodology).

**D. Carbon Capture and Storage (CCS) (34 percent of abatement potential, around 520 $MtCO_2e$ per year).** In this category, retrofitting CCS could abate around 300 $MtCO_2e$ per year and new builds around 220 $MtCO_2e$ per year. CCS isolates $CO_2$ after it has been emitted from a point source such as a blast furnace through injection into deep geological formations for permanent storage. The capture would occur after combustion, with chemical reactions cleaning the exhaust gases of $CO_2$. CCS is assumed to be applicable only for the integrated method of steelmaking. CCS is an immature technology today, and abatement potential will be limited by the possibilities for scaling up production and engineering skills. We assume that, for newly built steel plants, CCS would yield a 90 percent capture rate of $CO_2$ and 72 percent of new-build plants would be equipped with CCS in 2030 (90 percent of plants reaching sufficient scale and 80 percent of plants located close enough to a potential storage area). For retrofit CCS, many older plants are excluded from the potential because of technological constraints, leaving 40 percent of older plants suitable for CCS. Around 25 percent of all steel mills are expected be equipped with CCS in 2030. We should note that these numbers are dependent on the technology becoming industrially and commercially viable, which is yet to be proven.

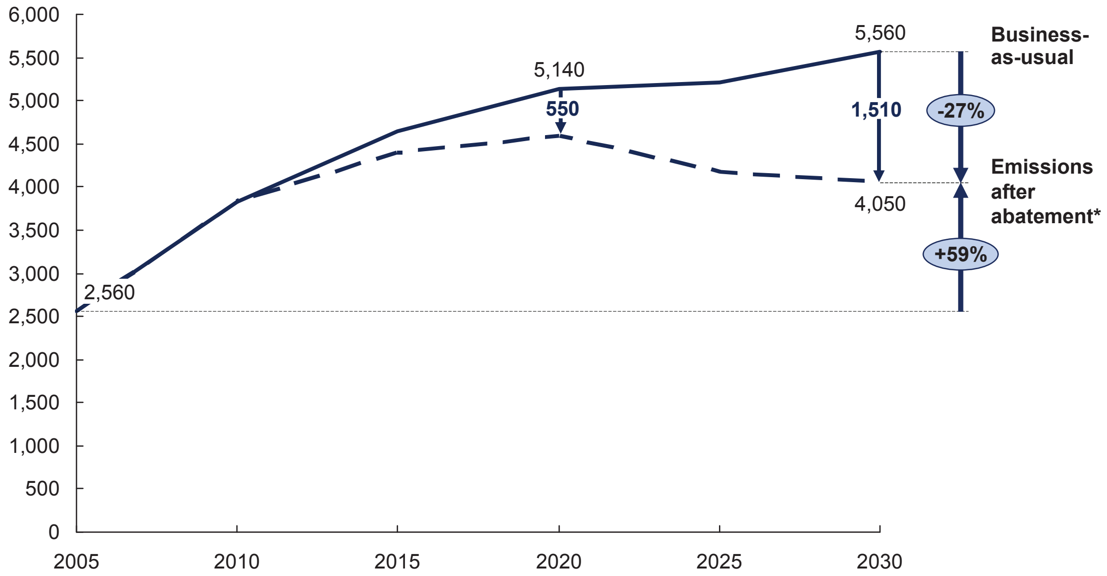
The identified abatement measures for the Iron and Steel sector can eliminate 1.5 $GtCO_2e$ per year worldwide by 2030, lowering industry emissions to 4.1 $GtCO_2e$ per year. This is a 27 percent reduction from the BAU case and would reduce 2030 emissions to the same level as 2010 emissions. The potential abatement volume increases over time due to an increasing implementation rate of the measures (Exhibit 8.4.2).

The investment needed to achieve the total abatement potential for the Iron and Steel sector is around € 23 billion per year from 2011 to 2020, increasing to about € 34 billion per year in 2021 to 2030 with the adoption of CCS that we have modeled. The global average cost is about minus € 2 per $tCO_2e$ in 2015, turning positive thereafter and increasing to about € 17 per $tCO_2e$ by 2030, mainly due to CCS. Taking the abatement levers individually, they range from offering negative costs to society and imposing positive costs. Fuel substitution from coke to biobased material such as charcoal could come at a negative cost, although this depends on the future relative price of these fuels. Energy-

**Exhibit 8.4.2**

## Emissions development for the Iron and Steel sector

$MtCO_2e$ per year




* Economic potential of technical measures

Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

efficiency measures and process change can require high upfront investments but typically between 30 and 50 percent of these measures can be realizable with limited investments. Such measures lead to both operational cost savings (fuel savings) and $CO_2$ abatement. CCS will require high capital and operational investments, since transportation of $CO_2$ incurs an operational expense.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | -2 | 23 | -7 |
| **2020** | -2 | 31 | -17 |
| **2025** | 14 | 33 | -11 |
| **2030** | 17 | 34 | -9 |

After abatement, carbon and energy intensity will converge but still vary across regions due to different production techniques (e.g. different relative shares of BF/BOF versus EAF) and pollution policies. China, for example, could realize a reduction of 35 percent in carbon intensity, down from 2.7 to 1.7 $tCO_2e$ per tonne of steel, whereas in North America the reduction would be from 1.4 to 1.1 $tCO_2e$ per tonne of steel.

## Implementation challenges

The analysis above is based on a "constraint-free" viewpoint but it is the case that commercial, technical, organizational, and regulatory challenges need to be addressed. In order for the iron and steel industry to adopt abatement measures, players must be able to realize economic benefits, either directly or by avoiding penalties. Additionally, the necessary state-of-the-art technology must be available. Significant changes to the business environment must occur if a truly radical transformation of the industry is to occur.

- **Capturing energy efficiency.** Improving energy efficiency and driving towards more energy-efficient processes has been, and will remain, one of the focuses of the Iron and Steel industry. Recent work to identify attractive energy-reduction options has consistently shown that significant potential, typically in the order of 10 to 15 percent of total energy costs, can be captured with paybacks of less than two years. These energy savings necessarily result in lower GHG emissions too. The primary barriers to realizing these opportunities are typically organizational. Given sufficient cost pressure due to a softening market environment or significant energy-price escalations, companies are likely to pursue these net-profit-positive abatement opportunities. We have therefore accounted for this potential in the BAU baseline.
- **Significant investment requirement.** Most companies already understand the rationale of switching to different approaches to cast and roll some specific steel products, e.g., direct casting. However, such technology changes may imply high switching costs and some level of risk, particularly if market conditions are uncertain or credit tight. When we also factor in cost escalations due to deteriorating raw-material quality, cash availability for large-scale investments can become a real constraint. Over the long term, positive returns on projects of this type are likely to enable a gradual migration to these technologies; the challenge lies in finding the right incentives to encourage them to move ahead more quickly.
- **Regional competitive effects.** Current regional competitive differences could further increase due to potential asymmetric regulations. This would pose an even greater challenge to those players that today suffer from competitive disadvantages as they seek to change from the status quo and adopt emission-reduction technologies that come at a net cost. It is therefore likely that some kind of incentive mechanisms or interventions will be needed to enable necessary shifts to take place.
- **Technologies and infrastructure maturity.** CCS technology holds great promise for emission reductions but this technology is still in the earliest phases of development and is unlikely to be ready for rollout in the industry until at least 2020.

## 8.5 Chemicals

The Chemicals sector contributes significantly to climate change by being directly responsible for about 15 percent of all global industrial GHG emissions, or about 2.4 $GtCO_2e$ per year in 2005 (corresponding to around 4 percent of all man-made GHG emissions, including indirect emissions).[59] Emissions are forecast to increase by 122 percent to 5.3 $GtCO_2e$ per year in 2030, which on an annual basis (3.2 percent) is only slightly below the forecast for Chemicals demand growth (3.4 percent). A significant portion of this growth – approximately 28 percent – stems from ozone-depleting substitutes (ODS), which are unique in that they arise not as a byproduct of chemicals production but rather are released at the end of their lifecycle from downstream products using them (e.g., refrigeration units). If the Chemicals industry implemented all identified abatement levers by 2030, it would reduce emissions by about 2.0 $GtCO_2e$ per year (a 38 percent decrease compared with the BAU case). Emissions would stabilize at 3.3 $GtCO_2e$ per year, corresponding to 2015 levels. Abatement in Chemicals is characterized by high upfront investments but also by large and increasing operational-cost savings as a result of reduced energy needs and increasing energy prices. Given its strong position in chemicals production and the comparatively high intensity of its emissions, China has both the highest share of emissions and an even greater share of the abatement potential (about 40 percent).

The chemicals industry has substantially reduced its GHG-emissions intensity over the last 15 years. Since 1990, while chemical-industry volumes have grown by 3.2 percent a year, emissions have increased by only 1.7 percent annually. The reason for this is largely improved energy efficiency, debottlenecking, improved asset utilization, and other active measures to reduce GHG emissions. However, there are regional variations. While Europe and North America demonstrate little or no absolute emissions increases, developing countries and other regions have significantly increased their emissions, mostly driven by strong volume growth.

### Business-as-usual emissions

Chemical sector emissions are expected to grow at an annual rate of about 3.2 percent through 2030 in the BAU case (i.e., without abatement measures), fuelled both by strong production growth and by

59 Indirect emissions represent 0.8 and 1.6 $GtCO_2e$ in 2005 and 2030, respectively

a shift in production to more carbon-intense regions, especially China. China will increase its share of global chemicals production from 27 percent in 2005 to 34 percent in 2030.

The rapid decarbonization of chemicals production that we have seen in recent years is not expected to continue at the same rate due to the declining marginal effect of efficiency measures and a shift of production to Asia, where coal is increasingly used as the primary fuel. Looking ahead, only a 0.2 percent annual decarbonization is believed to be achievable unless the more aggressive actions to reduce the carbon footprint from the chemicals industry described in this report are undertaken. Total BAU case emissions from the Chemicals sector will grow to about 5.3 $GtCO_2e$ per year in 2030, an increase of 122 percent compared with 2005.

We can split emissions from the chemicals industry into three categories:

- **Process emissions** released directly during the production process (often stoichiometric releases) accounted for around 40 percent of total chemicals emissions in 2005. Current emissions are calculated based on production volumes of selected chemicals that release GHGs during the production process (e.g., adipic acid, nitric acid, and ammonia). For each production process, region-specific emissions factors are used to calculate emissions (mostly from IPCC data). Future emissions are forecast to grow proportionally with production volumes (based on American Chemistry Council projected growth rates). A significant portion of process emissions (approximately 47 percent in 2030 in the BAU case) are associated with ODS substitutes, the set of products developed to replace hydrochlorofluorocarbons (HCFCs), largely in refrigeration applications. These emissions are unique in that they are not byproducts occurring at the production site but rather the emissions of the chemical products themselves when the downstream products of which they are a part reach the end of their lives. Thus, abating these emissions is out of the direct control of the Chemicals industry and rather must be achieved through improved recycling initiatives and the like.
- **Direct emissions** from fuel combustion to generate heat and/or electricity at the production site accounted for about 26 percent of 2005 emissions. To assess current emissions, we use IEA country data on fuel consumption of the chemicals industry and specific emissions per fuel. For future emissions, we assume that growth is in line with production forecasts, minus BAU energy-efficiency measures.
- **Indirect emissions** released by the Power sector but caused by the Chemicals industry by consumption of electricity accounted for some 34 percent of 2005 emissions. Similar to the calculation of direct emissions, we calculate the baseline of current indirect energy need using IEA data. We derive the carbon intensity of electricity from the Power sector model; future emissions include BAU decarbonization in the Power sector and energy-efficiency improvements in the Chemicals sector.

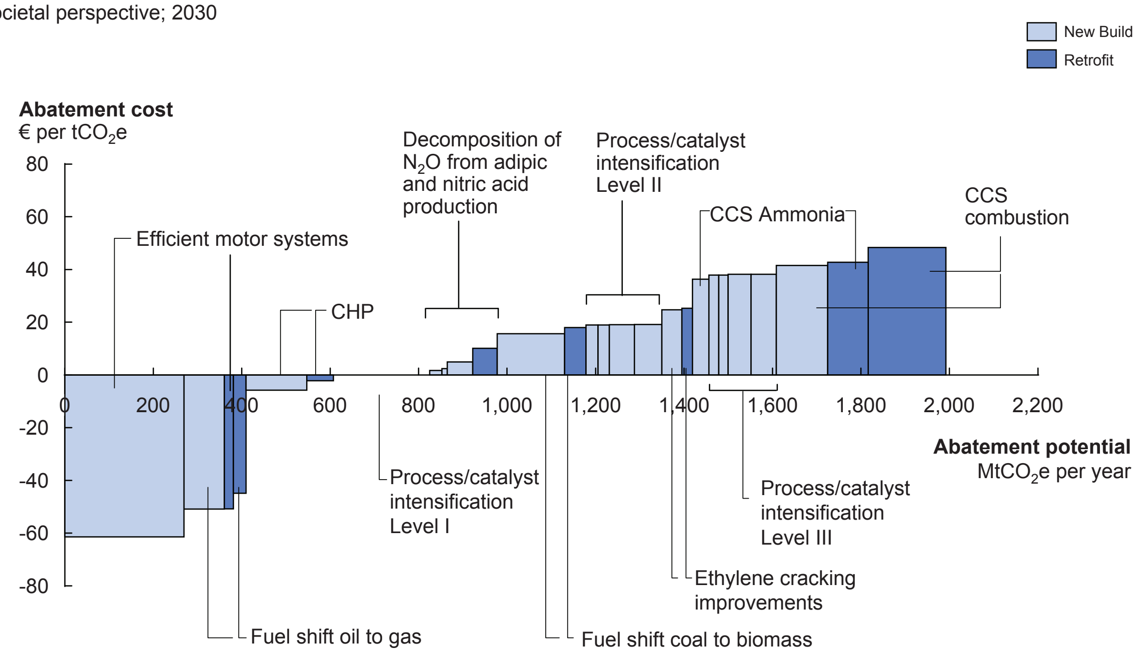
### Potential abatement

The global Chemicals industry can achieve a substantial reduction in its emissions by 2030 through concerted abatement efforts. While some of the measures we have identified will be net-profit-positive (and will at least partially occur as part of the BAU case), other steps will require a considerable financial and technological effort.

**Exhibit 8.5.1**

## Global GHG abatement cost curve for the Chemicals sector

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

We have identified 30 abatement measures that we can group in four categories (Exhibit 8.5.1):

**A. Energy efficiency.** At about 1,100 $MtCO_2e$, energy-efficiency measures contribute 55 percent of the total abatement potential, and are mostly net-profit-positive. Examples include motor systems, combined heat and power (CHP), ethylene-cracking improvements, and the optimization of catalysts.

**B. Fuel shift.** About 320 $MtCO_2e$, or 16 percent, of the total abatement potential, can be achieved by increasing the share of alternative, cleaner fuels, for example from oil to gas and from coal to biomass. Most of the measures in this category come at a relatively low cost or offer a net benefit to society. If fuel-shift efforts are undertaken aggressively, about 50 percent of the current use of coal can be replaced with biomass by 2030, taking total global demand and supply into account.

**C. Carbon Capture and Storage (CCS)** – CCS in the chemicals industry is estimated to account for a possible 21 percent of total abatement potential, or around 420 $MtCO_2e$). CCS is a new technology that sequesters $CO_2$ after it has been emitted from a point source in the production cycle through methods such as placing it in subterranean storage. Two different CCS technologies are applicable to the Chemicals sector: the capture of a pure $CO_2$ stream coming from ammonia production; and the capture of $CO_2$ from fuel-combustion emissions, similar to CCS in the Power sector.

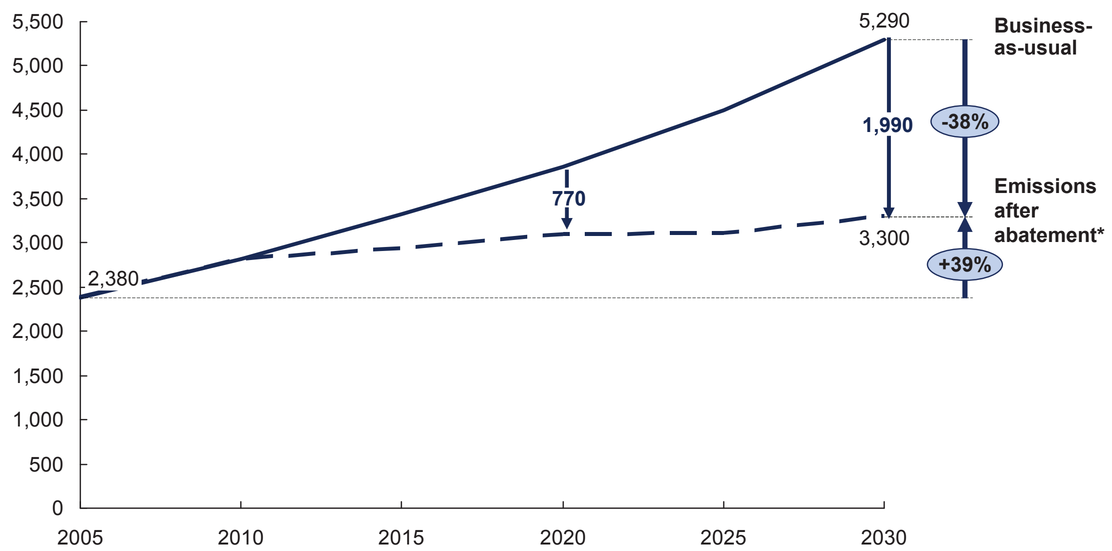
**D. Decomposition of non-$CO_2$ GHG gases.** The destruction of highly potent GHGs accounts for roughly 8 percent, or 150 $MtCO_2e$, of the abatement potential in the Chemicals sector. Levers in this category include the decomposition of $N_2O$ that accrues in the production of the common chemicals nitric acid and adipic acid.

The identified abatement measures for the Chemicals sector would eliminate approximately 2.0 $GtCO_2e$ per year worldwide in 2030, a 38 percent reduction from the BAU case. However, 2030 emissions after abatement would still be 39 percent higher than in 2005, due to high production growth (Exhibit 8.5.2). The inherent energy intensity of Chemicals implies that the industry will be unable to further reduce its emissions footprint without significant technological breakthroughs in clean energy.

**Exhibit 8.5.2**

**Emissions development for the Chemicals sector**

$MtCO_2e$ per year




* Economic potential of technical measures

Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

A further abatement potential of possibly several hundred megatonnes $CO_2e$ per year in 2030 could be achieved through the replacement of ODS substitutes used in refrigeration, air conditioning, and foam blowing agent application, but we have not assessed this possibility in depth in this analysis. Currently, Hydrofluorocarbons (HFCs) with global warming potentials (GWP) of over 1,000 are mostly used as ODS. However, several replacement products with GWP close to zero are being made commercially available, including, for example, automotive air conditioning and one-component foam blowing agents for insulation, which would reduce emissions dramatically.

For the abatement measures in this sector in aggregate, the cost would be negative at the outset at *minus* € 3 per $tCO_2e$ in 2020, but would turn positive during the period of our analysis, increasing to around € 5 per $tCO_2e$ in 2030. This increase is caused primarily by the introduction of CCS, which is a high-cost lever. There large potential overall of about 600 $MtCO_2e$ that would offer net benefits to society through fuel shift, the replacement of motor systems, and CHP. Abatement in the Chemicals sector as a whole is characterized by high upfront investments followed by large and increasing savings of operational costs. The abatement case calls for a total of € 520 billion in capital investment from 2010 to 2030. During this timeframe, operational cost savings of about € 280 billion can be realized through savings of energy, primarily fuel.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | 0 | 24 | -7 |
| **2020** | -3 | 24 | -15 |
| **2025** | 5 | 29 | -15 |
| **2030** | 5 | 27 | -20 |

There are broad regional variations in carbon and energy intensity within the Chemicals industry. While China and the rest of the developing world currently show significantly higher carbon intensities than Western countries, this difference is expected to decline over time as production technologies are improved and standardized globally, and abatement levers are implemented in developing regions.

The biggest abatement potential exists in regions with higher carbon intensities. For example, about 40 percent of the total abatement potential is in China, primarily due to an expected shift to biofuels and the implementation of CCS. Investment in abatement levers in the developing world also yield a higher return than in developed countries. For instance, China represents less than 36 percent of total investment requirements for its 40 percent share of the total potential in 2030.

## Implementation challenges

Some conditions must be put in place for the Chemicals sector abatement levers to succeed in reducing emissions:

- **Development and availability of alternative fuels.** Shifting from oil to gas and from coal to biomass is a key step in reducing carbon emissions. In certain regions, ensuring adequate supplies of biomass in order to replace oil as the primary fuel for production could be challenging.
- **Technology and infrastructure.** CCS is a nascent technology that has yet to be tested adequately tested for use in the chemicals industry. CCS is not expected to be rolled out until 2020.

### 8.6 Transport

The Transport sector consists of four subsectors: road, sea, air, and rail transport. Road is the largest subsector in size (accounting for 71 percent of GHG emissions in 2005) and, as a result, we have conducted a detailed bottom-up analysis of this subsector. Sea (17 percent) and air (10 percent) are the next biggest subsectors. For both of these subsectors, we have estimated abatement potential and costs based on a set of individual measures in a top-down approach. Given the small size of rail emissions (2 percent) and the relative efficiency of this subsector compared with others, we do not cover this subsector in this analysis.

#### ROAD TRANSPORT

The Road Transport sector emits 5.0 Gt$CO_2$e per year, contributing 12 percent of global emissions of GHGs in 2005. Around 60 percent of global road transport emissions currently originate from North America and Western Europe. In the absence of abatement measures, emissions from the road transport sector are projected to increase to 9.2 Gt$CO_2$e per year in 2030, mainly driven by an annual increase in vehicles of around 7 percent in the developing world. With new car sales in 2030 incorporating a combination of all currently known abatement measures, total fleet emissions can be lowered by about 30 percent, stabilizing at 2016–2020 levels. Most of the abatement potential derives from the use of existing technologies to make internal combustion engine-based vehicles more fuel-efficient. In addition, biofuels, hybrid vehicles, and electric vehicles also play an important role in emissions abatement. On average, abatement is net-profit-positive to society as fuel savings overcompensate for initial investments.

The Road Transport sector comprises all GHG emissions "well-to-wheel", including emissions related to the production of fuel ("well-to-tank") and fuel combustion emissions ("tank-to-wheel"). Total emissions in 2005 were 5.0 Gt$CO_2$e per year, of which 4.4 Gt$CO_2$e were emissions from combustion.

This analysis segments road vehicles into three types:[60]

- **Light-duty vehicles (LDVs)**, i.e., passenger cars and commercial vehicles of up to 3.5 metric tonnes, totaling 728 million vehicles worldwide and emitting 2.7 Gt$CO_2$e per year in 2005, or 257 g $CO_2$ per km (tank-to-wheel, real figures for fleet).

60 We exclude buses and two/three-wheel vehicles from the analysis because of minimal global shares of emissions.

- **Medium-duty vehicles (MDVs)**, defined as trucks with 3.5–16 metric tonnes in weight (e.g., delivery trucks), totaling 38 million vehicles emitting 0.7 $GtCO_2e$ per year in 2005.
- **Heavy-duty vehicles (HDVs)**, defined as trucks greater than 16 metric tonnes in weight (e.g., long-haul freight trucks), totaling 20 million vehicles emitting 1.0 $GtCO_2e$ per year in 2005.

Road transport is characterized by numerous mobile sources of emissions. Light-duty vehicles are largely privately owned, while medium- and heavy-duty vehicles are usually owned by commercial enterprises. Vehicles from all segments potentially can use different fuel types, such as gasoline, diesel, biofuels, electricity, or various fuel mixes.

Two-thirds of global road transport emissions currently come from developed countries, which accounted for 76 percent of LDVs in 2005. The United States has the largest vehicle fleet by far at 220 million LDVs (30 percent of the worldwide total), 3.5 million MDVs, and 4 million HDVs (20 percent of the total).

Emissions intensity varies greatly among regions. At 40 and 30 percent, respectively, Africa and North America have the highest average carbon intensity per km travelled, exceeding some European countries.

### Business-as-usual emissions

The BAU case (i.e., without abatement of emissions) for the Road Transport sector shows emissions growing by 83 percent overall through 2030, reaching 9.2 $GtCO_2e$ per year (8.1 from tank-to-wheel emissions). The BAU case includes only powertrain technologies already available in the marketplace. Minor fuel-economy improvements are included in the BAU case, as older vehicles in the fleet are retired and replaced. The BAU case includes an increased share of bioethanol and biodiesel in the global fuel mix after 2010, based on fulfilling existing legislative mandates.[61]

BAU growth through 2030 is driven by an increased number of vehicles, resulting in a higher total distance travelled, especially in the developing world and by commercial vehicles. The number of LDVs globally will nearly double, and the number of MDVs and HDVs will more than double:

- **LDVs** – 1,321 million vehicles worldwide emitting 4.3 $GtCO_2e$ (tank-to-wheel) per year in 2030.
- **MDVs** – 97 million vehicles emitting 1.5 $GtCO_2e$ per year.
- **HDVs** – 45 million vehicles emitting 2.3 $GtCO_2e$ per year.

Annual kilometers travelled worldwide will increase by 78 percent for LDVs, 166 percent for MDVs, and 117 percent for HDVs in 2005–2030.[62] Nearly all of this expansion will be driven by growth in the vehicle fleet, since average distance travelled per vehicle is forecast to increase by less than 10 percent by 2030. Slightly more than half of vehicles will be used in the developing world in 2030. China is forecast to have the world's largest vehicle fleet in 2030 at 285 million LDVs (22 percent of the worldwide total), 37 million MDVs (38 percent of total), and 10 million HDVs (21 percent of total), thus overtaking the United States.

61 BAU case biofuels feedstock is limited to first-generation agricultural feedstock (grain ethanol, sugarcane ethanol, palm diesel, rape seed diesel and soy diesel).

62 Assuming 2005's vehicle mix through 2030.

Road transport emissions will grow strongly in Asia; China accounts for almost half of the total emission growth through 2030, while India accounts for another 14 percent. Emissions from North America and Europe will remain relatively stable, with annual growth of only 1.2 percent. Because of its large emissions base in 2005, the United States will continue to represent a large proportion of total emissions. The United States and China together will account for 47 percent of 2030 emissions.

The BAU case is based on data from proprietary McKinsey automotive research, the International Energy Agency/World Business Council of Sustainable Development, the California Environmental Protection Agency, and comprehensive industry expert discussions.

## Potential abatement

We can divide technical abatement levers in Road Transport into five groups:

**A. Conventional internal-combustion engine (ICE) improvements.** The fuel efficiency of internal-combustion engines, whether spark (gasoline) or compression (diesel) ignition, can be significantly enhanced through technical enhancements made to both powertrain (e.g., downsizing and turbo-charging) and non-powertrain systems (e.g., vehicle-weight reduction). Those improvements will drive most change on a per-car basis. The overall fuel-efficiency benefit is calculated using a combination of improvements, taking into account some cross-measure cannibalization. Powertrain measures for gasoline LDVs include variable valve control (about an 8 percent fuel-efficiency gain), strong engine friction reduction (around 4 percent gain), strong downsizing (some 12 percent gain), and homogeneous direct injection (approximately a 4 percent gain). Non-powertrain measures for gasoline LDVs include low rolling resistance tires (around 2 percent gain), tire pressure control system (about a 1 percent gain), strong weight reduction (approximately a 6 percent gain), pump and steering electrification (about a 3 percent gain), air conditioning modification (about a 2 percent gain), optimized transmission/dual clutch (around a 6 percent gain), improved aerodynamics (a gain of approximately 1 to 2 percent) and start-stop system with regenerative braking (6 percent gain). Diesel ICE measures are similar.

For MDVs and HDVs, we define bundles in a similar manner. Measures include varying degrees of rolling-friction reduction (around a 3 percent gain), aerodynamic improvements (a gain of some 1 percent), and conventional ICE improvements such as mild hybrid powertrains (approximately a 7 percent gain). Commercial vehicles are further along the learning curve of fuel consumption since fuel spending is of substantially higher importance than for LDVs; therefore the relative improvement potential is lower.

The calculations in this study only take into account technical measures that are already widely known to experts, and where there is a substantial likelihood of significant adoption. By definition, this eliminates consideration of “game changing” new technologies that could drive substantial abatement or accelerate fleet changeover. While we do not consider these factors in this particular estimate, we do believe that the chances of such discontinuity are significant and should be considered by all stakeholders when evaluating long-term abatement potential.

**B. Hybrid vehicles.** Hybrid electric vehicles take many forms. Hybrids on the road today range from mild, simply incorporating some form of a stop-start system, to full, where an electrical drive system is packaged in parallel to the ICE drive system and is calibrated to run when conditions best suit electrical driving. In addition, full hybrids are typically engineered in such a way that aerodynamic drag, rolling resistance, and weight are all reduced to varying degrees. The full hybrid battery is charged by the drive cycle of the vehicle (e.g., regenerative braking).

A further hybrid development will be the introduction of "plug-in hybrids", i.e., full-hybrids that can be recharged both by the vehicle-driving cycle and by external sources, enabling the vehicle to run more frequently on electrical power. Vehicle emissions may well be reduced with such a vehicle compared to an equivalently sized ICE or full hybrid, but total carbon emissions will depend on the $CO_2e$ intensity of the electricity drawn from the grid. Consequently, electrified vehicles will save gasoline, but substantial reduction of carbon emissions can only be achieved with substantial changes in the power mix.

For both types of hybrids, the abatement potential will be based on the share of electric driving dictated by the vehicle's drive cycle (e.g., rural versus urban) and opportunities to recharge (in the case of a plug-in hybrid). One critical assumption for plug-in hybrids is that the owner will not need to replace the battery during the lifetime of the vehicle. Plug-in hybrids must handle both full charging cycles when an almost empty battery is connected to the grid, and micro cycles when the battery receives energy from the brakes while driving. While batteries today are believed to already handle enough full charging cycles that last longer than a normal vehicle, the impact of micro cycles on battery lifetime is not fully understood.

C. **Electric vehicles.** Despite being very much in their infancy in terms of market penetration, range-worthy (battery) electric vehicles (EVs) are gathering significant momentum as battery innovators develop the nanotechnology and chemistry that will be required to create the energy density needed to give these vehicles the range desired by consumers. EVs are powered by an electric motor that receives power, via a controller, from a battery of significant capacity. Much progress is anticipated in terms of cost, energy density, and charging infrastructure, making EVs feasible in terms of cost and consumer convenience and significantly enhancing the opportunity for EVs to become mainstream. The abatement potential from EVs depends on the $CO_2e$ intensity of electricity drawn from the grid.[63] In the outlook for 2050, with an even greener power mix, strongly electrified vehicles may play a very important role in achieving a step change in the reduction of transport emissions.

D. **Compressed natural gas (CNG) vehicles.** These vehicles run on an ICE (fairly similar to gasoline and diesel engines) fueled by CNG. The abatement potential originates from the lower $CO_2e$ intensity of natural gas compared to other fossil fuels. However, long-distance pipelines for sourcing natural gas can potentially offset the $CO_2e$ advantage.

E. **Biofuels.** Fossil fuels can be replaced by first-generation biofuels, such as bioethanol (from food feedstock), biodiesel (from vegetarian oils) and biogas, or by second-generation biofuels based on lignocellulosic biomass (e.g., lignocellulosic (LC) ethanol, Fischer-Tropf (FT) diesel, and dimethyl ether (DME)). The abatement potential varies depending on the biomass used for biofuel production (with respect to agricultural and process emissions), and on the potential for land-use change emissions associated with increased crop production.

- ***First generation biofuels.*** The most prevalent first generation biofuel today is bioethanol. It can be derived from various feedstocks such as corn, wheat and sugarcane, with sugarcane being by far the best first-generation bioethanol option in terms of cost and GHG reduction. First-generation biodiesel is derived from oil crops such as palm oil, rapeseed, soy beans, and recycled waste oils and fats. These first-generation products do provide abatement opportunities. However, they will have to have been produced from sustainable feedstock and produced in a way to avoid land-use change or displacement of other products into unsustainable production, e.g. via yield increases or using "idle land" (see fact box Biofuels).

63 Calculations assume the emissions intensity of the power mix after abatement.

Biogas is another option that can be a promising biofuel; however scalability at competitive cost appears limited.

- ***Second-generation biofuels.*** Second-generation bioethanol is derived from lignocellulosic feedstock such as bagasse, wheat straw, corn stover, or dedicated energy plants such as switch grass, and have a $CO_2$ reduction potential of up to 90 percent. Although not commercially viable today, significant research and development efforts could bring production costs down to a competitive level. Second-generation biodiesel can be derived from various other feedstocks, including wood, energy crops such as switchgrass, and algae. Biofuels from these feedstocks are likely to coexist by 2030. Second-generation biofuels may also include syngas-derived DME or FT gasoline and diesel. Given regional differences in demand for, and government support of, gasoline and diesel substitutes, technologies targeting either fuel are expected to emerge.

**Biofuels – some upsides and potential downsides**

**Upside.** Algae are a promising feedstock, which could grow in areas that do not compete with food or fresh water. To date, commercial algae production has focused on niche markets such as nutraceuticals and therefore technological development for commodity fuels markets is in its infancy. This current uncertainty is believed to be too high to warrant inclusion in the cost curve. However, if the required developments were to be realized, the potential upside would be very large and algae could pick up a significant share of the transportation fuel pool. The promise of a large volume of low-cost algae bio-diesel has already triggered intense research efforts.

**Potential downside.** Land-use change caused $CO_2$ emissions can have strong adverse effects on the sustainability of biofuels. As production volumes of biofuels expand, it will be key to implement standards and regulations that ensure that land is used in a sustainable manner. Besides direct land-use change, indirect land-use change also needs to be considered. Policies should be based on globally consistent methodologies for assessing impacts and should encourage production that minimize negative *direct* land use change effects and hence negate the possibility of indirect impacts. Such practices include yield intensification or the use of marginal land.

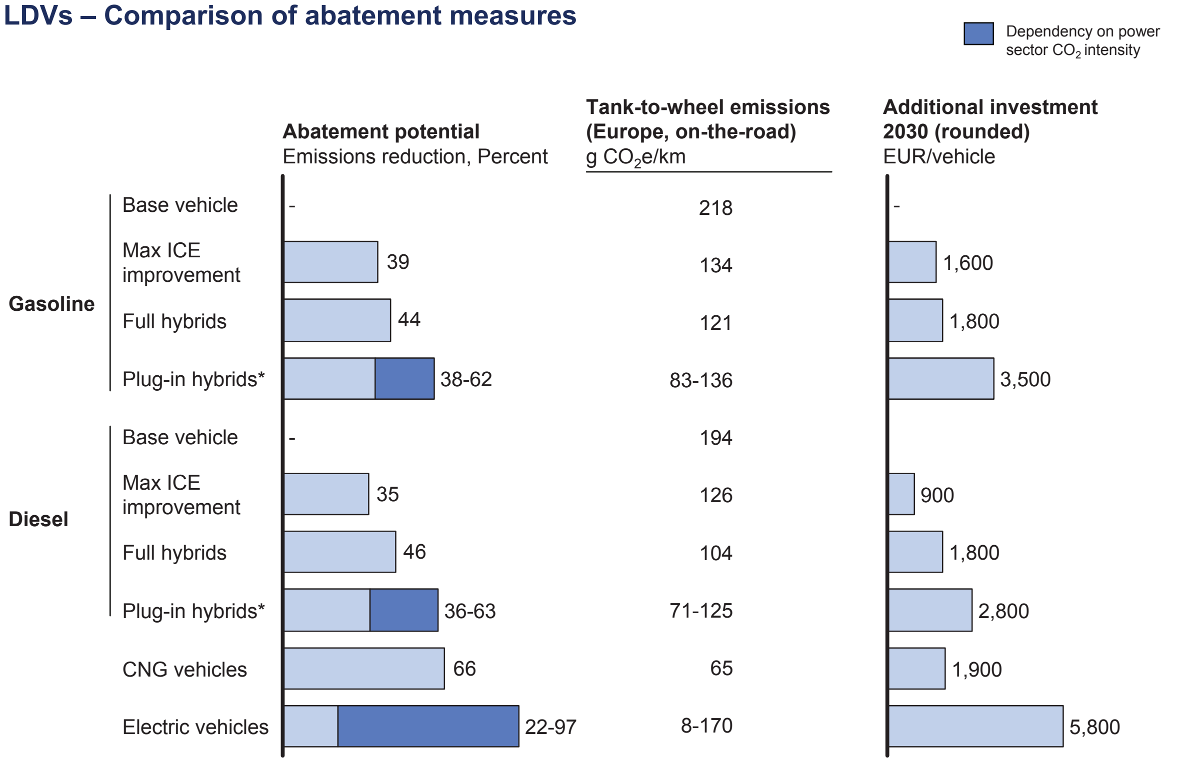
Beyond these five groups of abatement levers, hydrogen vehicles are a nascent technology that could prove an alternative solution. Based on current knowledge, the abatement cost is extremely high and for this reason hydrogen vehicles have not been considered in the cost curve.

In addition to the “known” technologies that have been considered for abatement calculations, there will undoubtedly be a number of breakthrough innovations that will not only further optimize what we know today, but will also advance the art of combustion and propulsion. In that light, our abatement scenarios may prove, in the long run, to be conservative. The automotive crystal ball is usually populated with more incremental developments than it is quantum shifts in technology, thanks in part to an industry that is risk-averse especially in terms of safety, quality, and cost. That said, significant investment is being deployed into the development of “clean-tech” solutions for automobiles as stiffer emissions-regulation looms, gasoline prices become increasingly volatile, and fuel economy becomes more of a reason for consumers to consider a vehicle.

All the powertrain and non-powertrain improvements come at an initial cost, and they lead in turn to substantial savings on fuel spending. For LDVs, the cost and emissions reduction potential of these levers are shown in Exhibit 8.6.1. The additional cost is relative to the cost of a “base vehicle” which

**Exhibit 8.6.1**

## LDVs – Comparison of abatement measures




* Assuming 66% electric share for Plug-in Hybrids
Source: Global GHG Abatement Cost Curve v2.0

is assumed to have a median or "typical traditional" powertrain for gasoline and diesel. For gasoline vehicles, which globally represent the vast majority of LDVs, a fuel consumption reduction of about 39 percent is possible with pure ICE improvements at an incremental cost of 10 percent of the vehicle base price. Full hybrids (including non-powertrain measures such as weight reduction) cost about 22 percent more than maximum ICE improvements, and can achieve a further 5 percentage points of fuel reduction. Substantially higher emission reductions of almost 100 percent are made possible by switching to plug-in hybrids and pure electric vehicles (if the local power sector has a very low emission intensity), at a substantially higher cost (of an additional 120 to 260 percent).

For biofuels, no extra cost to the vehicle is assumed, but there is a different cost structure and carbon-emission pattern of the fuel itself compared with fossil fuels.

**Scenario analysis.** The total road transport abatement opportunities are assessed using different scenarios, in a similar way to our analysis of the Power sector. The Road Transport sector exhibits a higher level of uncertainty than most other sectors for technology development and related cost, regulation, and consumer behavior and preferences. To develop scenarios, we applied different penetration shares of abatement options (ICE improvements, hybrids, electric, and CNG vehicles) for LDVs over time. These different penetration rates are used solely to illustrate the range of abatement potential and should not be considered a forecast or an endorsement of a specific technology. As an exception, the scenarios do consider levers with a cost in 2030 of below € 100 per $tCO_2e$, given the explicit knowledge of these technologies and the substantially higher regional cost range in the Transport sector. Biofuels are not affected by the scenario choices, as their potential is fully included in each scenario.

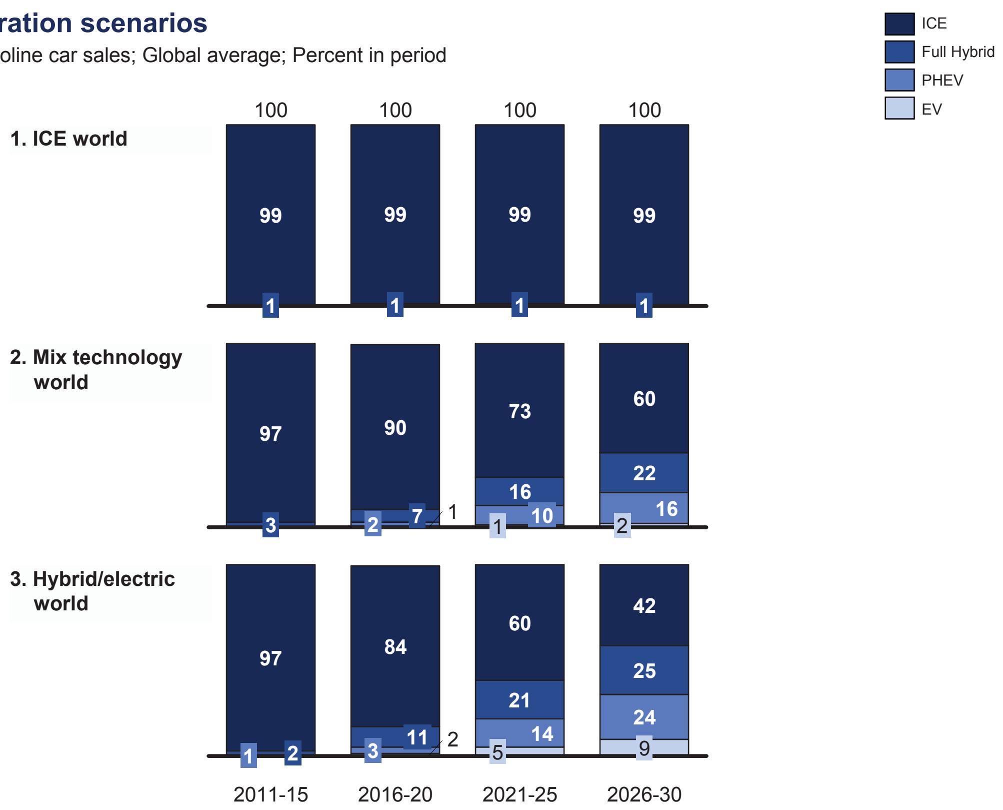
- **Scenario 1 – ICE World.** In this scenario, all new cars are ICE cars throughout the entire period. ICE improvement measures are implemented gradually, with all new cars equipped with the highest-efficiency measures starting in 2026.
- **Scenario 2 – Mix Technology World.** The vehicle-sales mix shifts from 90 percent ICE engines and 10 percent "other powertrains" in 2016–2020 to 40 percent "other powertrains" in the 2026–2030 period. In 2026–2030, full hybrids account for 22 percent of new sales and plug-in hybrids for 16 percent. In this scenario, electric vehicles are to replace 2 percent of gasoline vehicles. The penetration of new powertrains is based on consensus estimates.
- **Scenario 3 – Hybrid/Electric World.** The portion of hybrids and EVs in the sales mix ramps up from 16 percent in 2016–2020 to 58 percent in 2026–2030. In the final portion of the study period, 25 percent of sales are full hybrids, 24 percent are plug-in hybrids, and 9 percent are EVs. These rates represent expert expectations on maximum technical ramp-up potential for new powertrains.

The main uncertainty between the scenarios lies within the abatement-potential development for LDVs. Thus, the various scenarios reflect different penetrations for LDVs. All scenarios are designed to have a very high abatement potential. The mix of powertrains is the key difference (Exhibit 8.6.2). The shares of gasoline and diesel vehicles are held constant in each region, and penetration shares for new powertrains for diesel vehicles are similar to those of gasoline vehicles.

**Exhibit 8.6.2**

## LDV – penetration scenarios

Share of new gasoline car sales; Global average; Percent in period




Source: Global GHG Abatement Cost Curve v2.0

MDV and HDV penetration rates are the same in all scenarios. Starting in 2016, almost all new MDVs and HDVs will either have improved ICE powertrains – including reduced rolling friction and mild hybrid features – or be hybrid vehicles. Even in the BAU case, a significant share of commercial vehicles are equipped with some fuel- reduction bundles, due to the increased importance of fuel costs as a buying-decision criterion when compared with passenger cars. MDV/HDV full hybrids and plug-in hybrids both exhibit an abatement cost that is significantly above the cost-curve cut-off, and have therefore not been included in this analysis. This is true also for niche MDV segments, such as waste-collection vehicles where driving patterns and extra equipment mean that hybrid technologies would be able to significant improve fuel economy. Unfortunately, the configurations that would exhibit the highest fuel-economy improvements typically also require additional investments on top of the “basic” hybrid equipment. Buses are outside the scope of the analysis, but there seems to be significant potential for fuel-economy improvement for a full-hybrid city bus, since it would be a showcase application for a start-stop system with regenerative braking. This could lead to an abatement cost of below €100 per $tCO_2e$.

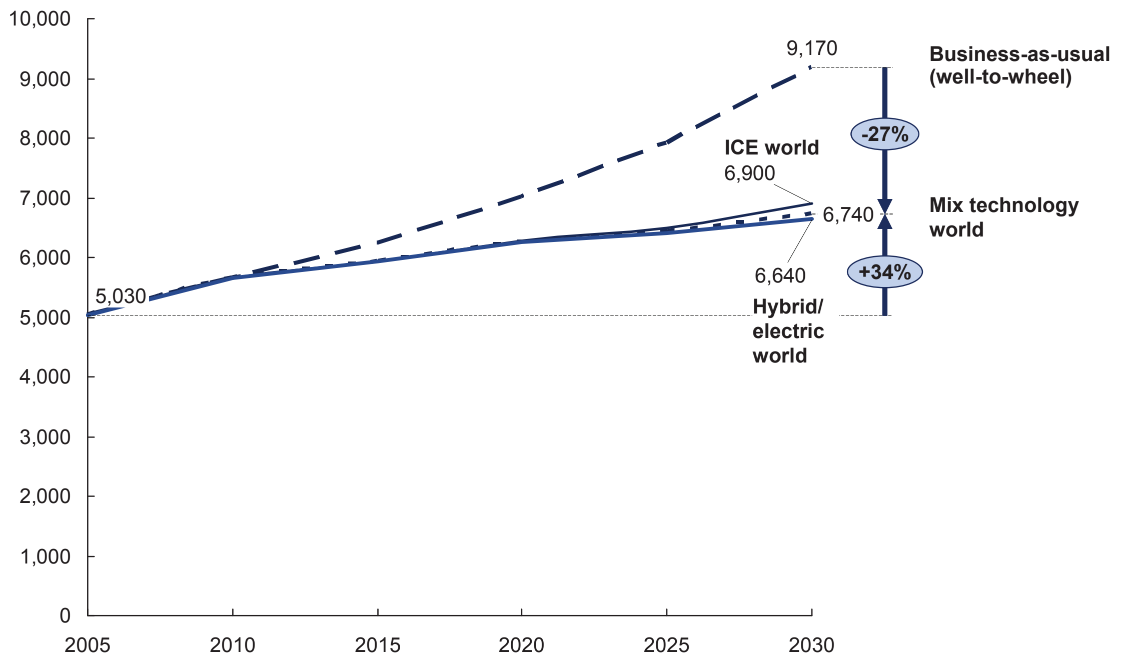
The three road transport scenarios lead to a 2030 abatement potential ranging from 25 to 28 percent (2.3 $GtCO_2e$ to 2.5 $GtCO_2e$ per year) for all vehicle types combined (Exhibit 8.6.3). For LDVs specifically, the ICE World scenario would lead to a 29 percent reduction in emissions (1.4 $GtCO_2e$ per year); the Mix Technology World offers a 33 percent reduction (1.6 $GtCO_2e$ per year); and 35 percent abatement (1.7 $GtCO_2e$ per year) can be achieved in the Hybrid/Electric World scenario. In all three scenarios, emissions for MDVs can be reduced by 8 percent from the BAU case, and by 9 percent in the case of HDVs. These abatement figures are lower than for LDVs, primarily because the possible further fuel-consumption reductions of ICE measures are substantially lower than for LDVs. Compared with 2005 levels (including refining emissions), emissions would increase by around 20 to 30 percent in all scenarios, driven by the significant growth of total distance travelled.

The biggest abatement potential is found in regions with the highest BAU case emissions, as one would expect. The United States and China account for the largest abatement potential, with 53 percent of total global emissions savings. After abatement, the United States and China together still account for 49 percent of emissions.

**Exhibit 8.6.3**

## Emissions development for the Road Transport sector

$MtCO_2e$ per year




* Economic potential of technical measures

Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

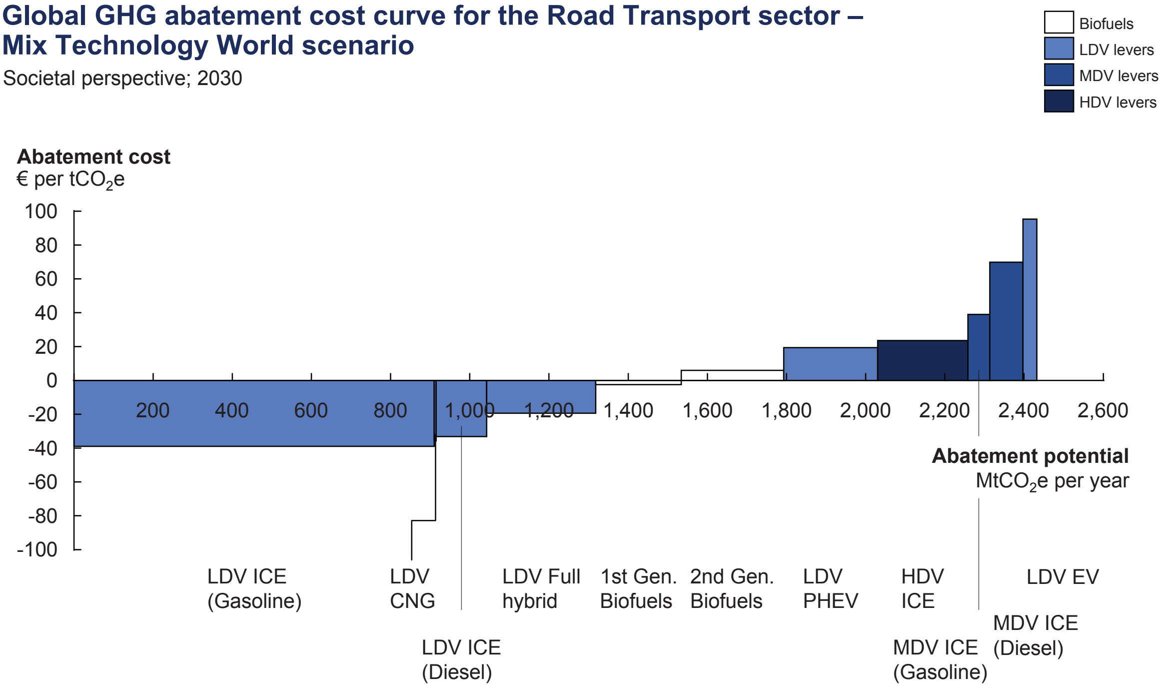
When comparing average cost of the scenarios, the range is minus € 17 to minus € 3 per $tCO_2e$ for all measures. For LDVs only, the ICE World scenario would cost on average minus € 38 per $tCO_2e$, the Mix Technology World minus € 24 per $tCO_2e$, and Hybrid/Electric World minus € 13 per $tCO_2e$.

To illustrate the effects of the individual lever categories, we show the cost curve for the Mix Technology World scenario in Exhibit 8.6.4. The cost for a specific lever is the cost compared with the BAU case, i.e., what the abatement cost would be to replace a median 2005 vehicle with a new vehicle as specified.

**Exhibit 8.6.4**

## Global GHG abatement cost curve for the Road Transport sector – Mix Technology World scenario

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €100 per $tCO_2e$ in a penetration scenario if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

Most abatement levers, particularly those concerning conventional ICE improvements, come at a benefit to society – i.e., there is a positive payback over the lifetime of a vehicle when subtracting fuel-cost savings from the initial additional investment into more emission-efficient vehicle technology. The cost curve shows that the majority (60 percent) of LDV abatement, excluding biofuels effects, can be achieved with technical improvements to ICE vehicles for fuel efficiency. Gasoline fuel efficiency bundles for LDVs have an abatement potential of 0.9 $GtCO_2e$ per year. Similarly, the diesel-efficiency bundles for LDVs show a 0.1 $GtCO_2e$ per year abatement potential. In this scenario, full hybrids account for 0.3 $GtCO_2e$ per year abatement potential, plug-in hybrids for 0.2 $GtCO_2e$ per year, and electric vehicles for 0.03 $GtCO_2e$ per year. Given a reasonably clean power mix, plug-in hybrids and EVs have substantially higher emission-reduction potential per vehicle than hybrids or ICE improvements. As further emission reductions beyond 2030 are required, these technologies will likely be needed to achieve the targets.

Biofuels to replace gasoline have substantial abatement potential. First- and second-generation biofuels account for around 20 percent of total abatement in 2030. For modeling purposes, ethanol was chosen to represent biofuels. First-generation bioethanol are modeled on sugarcane, since other crops are not expected to offer cost-effective abatement opportunities. Second-generation LC ethanol is modeled on a weighted average of feedstock. The BAU case includes 38 billion liters of biodiesel production; there is no additional biodiesel in the abatement case.

As we have discussed, there are several interesting options that we have not modeled, most notably second-generation biodiesel from algae and gasification-based diesel substitutes. The share of the gasoline-equivalent fuel mix is assumed to increase to 25 percent of energy content through 2030. This (ambitious) level was chosen as a technical limit for 2030; it corresponds to the current ethanol concentration in Brazilian gasoline (all regular Brazilian cars can run on this mix) and annual growth of about 15 percent in biofuel production.

Taking the Mix Technology World scenario as illustration, the total investment for road transport abatement levers in 2011–2030 is approximately € 3,050 billion, which is partly offset by savings in operating expenditures of approximately € 1,870 billion in the same period. Investments jump in the 2016–2020 period – all ICE measures are rolled out only then due to OEM lead times. Due to the fact that new vehicle sales and the highest penetration of new powertrain concepts occur in this period, investments peak in the 2026–2030 period at € 270 billion annually.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | 10 | 33 | -12 |
| **2020** | 4 | 107 | -53 |
| **2025** | -3 | 202 | -119 |
| **2030** | -10 | 269 | -190 |

**Abatement opportunities beyond technical vehicle improvements.** Beyond ICE improvements, hybrid vehicles, electric vehicles, and biofuels, there are several abatement opportunities that require no technical change in vehicles but rather action by individuals, companies, or governments. We can group these into three categories:

- **Behavioral changes by LDV consumers.** First, consumers can choose to buy smaller cars or cars with smaller engines and consequently lower fuel consumption. Second, they can change driving behavior to a more fuel-efficient style, i.e., reducing maximum speeds (since fuel consumption grows exponentially with speed), reducing fast accelerations, and avoiding unnecessary braking. Technical support for “eco-driving” exists, for example in the form of eco-lamp indicators as well as eco-driving training, which can increase drivers’ awareness. Third, driving less is a consumer choice. Alternative ways of transport (by foot, bicycle, or public transport) can be an option in many cases, as can car pooling.
- **Commercial transport improvements (MDVs, HDVs).** Emissions can be reduced through increased vehicle capacity, i.e., longer trucks, and increased utilization by better utilization planning. As illustration, if a segment of the long-haul general cargo HDV fleet were gradually replaced by longer trucks with a 50 percent higher load capacity (two vehicles replacing three), the abatement potential would be around 15 percent of emissions for that segment—in itself the same potential as all HDV ICE improvements together. If 35 percent of the global long-haul general cargo HDV fleet (long-haul general cargo assumed to account for 45 percent of all HDVs) were to be replaced, the abatement opportunity would be about 50 $MtCO_2e$ per year in 2030. Improved route planning, supported by IT systems, can help reduce distance driven. Choosing

the appropriate vehicles and engines for the commercial tasks would avoid "oversizing" of vehicles, leading to fewer emitting vehicles. Proper maintenance of vehicles would also have a positive effect on emissions and operating cost.

- **Traffic-system improvements for all vehicle types.** Governmental organizations have a wide range of options for influencing emission reductions. Intelligent transportation systems, such as Japan's Vehicle Information and Communication (VICS) System, improve traffic flow. Similarly, road design and construction has a substantial effect. Examples include improved crossing design, separate lanes for commercial vehicles, and electronic toll collection (ETC). Promoting modal shift from car to public transport and from road to rail for commercial purposes would boost emissions reductions. Especially in the developing world, where there are strong urbanization trends, urban planning with well-designed public transport has high potential. Lastly, regulatory levers such as lowering speed limits and introducing congestion charges (e.g., in London), can be introduced to achieve emissions reductions.

### Implementation challenges

To achieve success in abating road transport emissions, both economic and technical challenges need to be addressed:

- **Consumer preferences and non-rational economics.** Many factors influence the decision to buy a new car, including driving performance, design, and durability. Fuel consumption, and consequently emissions, is only one dimension for consumers when comparing vehicles. In addition, consumers usually do not thoroughly calculate and compare the economics of different vehicles when making their purchasing decisions. When they do so, they often overestimate the upfront investment compared to later savings.
- **Principal-agent problem.** Especially for light-duty vehicles, a gap exists between the socioeconomic perspective, the perspective of the individual vehicle buyer, and the OEM. Given the non-rational economics of the consumer, it is not clear to OEMs that buyers would be willing to pay the extra price for fuel-savings bundles, even when the consumer has the benefits. Therefore, these fuel-reduction options may not be implemented or offered.
- **Technology advancement.** Battery capacity and cost are the key factors limiting broad use of hybrid and full electric vehicles. Current technology restricts the range and speed of vehicles running on batteries and electric motors.

## AIR AND SEA TRANSPORT

Both Air Transport and Sea Transport are global sectors with the vast majority of emissions occurring in international territories. For this reason, we do not divide and attribute emissions to separate countries in this analysis (in accordance with established practice). Given their relatively small size, this study analyzed both sectors in a top-down manner for total emissions potential, cost, and investment, rather than a detailed bottom-up, lever-by-lever assessment.

**Air Transport.** Air Transport accounted for 0.7 $GtCO_2e$ per year emissions in 2005. Emissions are expected to grow by about 3 percent per annum to 1.5 $GtCO_2e$ per year in 2030. Ongoing efficiency improvements in fuel consumption mean that emissions will grow more slowly than air traffic, which is expected to increase by 5 percent annually. Measures costing less than € 60 per $tCO_2e$ have an abatement potential of 0.36 $GtCO_2e$ per year, or 24 percent, in 2030, and can be grouped into three categories:

- **Technology solutions including alternative fuels.** These abatement measures comprise aerodynamic improvements, engine retrofit and upgrades, accelerated fleet replacement, and reduced speed design. Alternative fuels considered are biofuels, gas to liquid, and, to a lesser extent, hydrogen, which is not expected to be commercially available before 2050. These measures come at a medium to high cost on top of the BAU case improvements and account for about 50 percent of the total sector potential for emissions abatement.
- **Operations-efficiency improvements.** This category includes improved fuel management, optimized take-off and landing procedures, taxiing with shut-off engines, cabin-weight reductions, and increased load factors. Taken together, some 35 percent of the sector's potential can be attributed to operational savings for this category, which can be achieved at low to medium cost.
- **Infrastructure and air-traffic management.** Air-traffic management, redesigned airspace, the flexible use of military airspace, and improved flight tracks account for about 15 percent of the sector potential and are net-profit-positive or low cost.

Since substantial efficiency improvements are already captured in the BAU case, the total abatement cost for the Air Transport sector is positive throughout the entire study period, falling slightly from € 16 per $tCO_2e$ in 2015 to € 13 per $tCO_2e$ in 2030, mainly because of increasing fuel costs. The required investments are € 21 billion per year in 2030 and about € 280 billion over the entire 2010–2030 period in order to capture the full abatement potential.

**Sea Transport.** The Sea Transport sector is forecast to emit 1.8 $GtCO_2e$ per year in 2030, with emissions growing by 2 percent a year from the 2005 level of 1.1 $GtCO_2e$ per year. Global sea transport is expected to grow at a higher rate of 3 percent annually. The difference is explained by more efficient hydrodynamics and machinery and an expected improvement in the load factor of ships.

A further emissions reduction of 24 percent, or 0.43 $GtCO_2e$ per year, can be achieved in 2030 through the implementation of two types of measures:

- **Technology solutions including alternative fuels.** Improved hydrodynamics levers comprise optimized hull shape, tailor-made propeller design, coating systems, and stern flaps. Machinery improvements include engine optimization and upgrades, waste-heat recovery, and a plant concept with multiple engines. Alternative fuels – marine diesel oil and biofuels – are viable ways to replace bunker fuels.
- **Operations-efficiency improvements.** This category includes increased vessel size and speed reductions, which increase ships' load factor.

Further measures on the horizon, including sky sails and semi-submerged ships that use ocean currents to power intercontinental transports, are excluded from this analysis.
In contrast to the Air Transport sector, emissions abatement in Sea Transport is net-profit-positive, given a lower efficiency starting position. In 2015, the cost will be *minus* € 5 per $tCO_2e$, which will further decrease to *minus* € 7 per $tCO_2e$ due to increasing fuel prices. About € 160 billion in investments is necessary in 2010–2030 to realize all abatement. Annual investments in 2030 are around € 10 billion.

## 8.7 Buildings

Buildings emitted 8.3 $GtCO_2e$ per year in 2005, accounting for about 18 percent of global GHG emissions and accounting for more than 30 percent of emissions in many developed nations. In the absence of abatement measures, global emissions from buildings are forecast to grow by 1.7 percent annually, increasing by 53 percent overall in 2005–2030. Carbon emissions in the Buildings sector can be substantially reduced, either with net economic benefits or at low cost, using a range of proven technologies centered on demand reduction and energy efficiency. Identified abatement measures would lower projected emissions in 2030 from 12.6 $GtCO_2e$ per year to 9.1 $GtCO_2e$ per year, with most developed countries reducing emissions to levels lower than those that prevailed in 2005. Currently, many of the abatement opportunities with net economic benefits are not realized due to misaligned incentives, high perceived consumer discount rates, information gaps, and program costs.

Energy usage in residential and commercial buildings is responsible for significant $CO_2$ emissions through a number of end uses: heating, ventilation, and air conditioning (HVAC); water heating; lighting; and appliances. Direct emissions from primary energy usage in buildings accounted for 3.5 $GtCO_2e$ per year in 2005, approximately 8 percent of global GHG emissions. Indirect emissions from buildings' power usage and district heat totaled 4.8 $GtCO_2e$ per year in 2005, or 10 percent of the global total.

Residential buildings, which include single-family homes and apartment buildings, account for 62 percent of the sector's overall emissions. Commercial and public buildings, which include a wide range of building types such as warehousing, food service, education, lodging, malls, and hospitals, are responsible for 38 percent of sector emissions. The overall lifespan of buildings is 35–70 years, depending on the type of building and geography, with 65–70 years being the average in developed countries. This long lifecycle leads to low or negative lifecycle costs for many abatement opportunities, but high upfront costs create a barrier to initial investments in energy efficiency. However, the long lifespan also means that decisions made during a building's construction (such as building orientation and insulation) have a strong lock-in effect for future emissions.

### Business-as-usual emissions

Energy consumption and associated emissions in the Buildings sector will grow significantly from 2005 to 2030, driven by steady growth in developed countries and rapid growth in developing countries such as China and India, where GDP growth is projected to exceed 5 percent annually. Globally, total floor space will grow from 137 billion $m^2$ in 2005 to 240 billion $m^2$ in 2030, an increase of some 75 percent.[64] There will be corresponding growth in HVAC usage, along with ownership of appliances and lighting.

64 Commercial and residential floor space with modern heating.

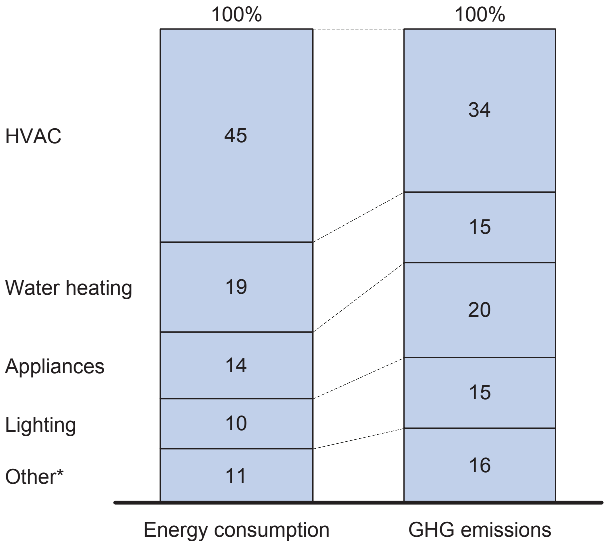
Our analysis assumes a BAU decarbonization effect in 2005–2030. For example, the share of high-efficiency gas/oil heater purchases in developed countries, at 29 percent in 2005, is expected to grow by around 2 percent annually under BAU to reach a 48 percent share by 2030. Direct and indirect emissions from buildings are expected to reach 12.6 $GtCO_2e$ per year in 2030.[65]

The analysis for technology-driven levers (e.g., appliances, lighting, and HVAC) considers items that have been proven in the market with predictable performance and cost. However, this analysis of the Buildings sector analysis excludes solar photovoltaics, which we capture in our analysis of the Power sector.

Combined heat and power (CHP) and district heating systems are also excluded as explicit abatement levers. A guiding principle in the Buildings sector analysis is to reduce overall heat and power demand through energy-efficiency levers (e.g., passive housing). Similarly, in the Power sector, the modelling approach is to maximize low-carbon solutions by using renewables, nuclear power, and CCS. After these levers are fully exploited in the Buildings and the Power sectors, our model does not show much additional abatement potential from CHP or district heating. While residential CHP is a viable interim solution to reduce emissions if favorable policy and regulatory incentives are in place, it shows limited potential in the long term when we consider the full spectrum of abatement opportunities.
The BAU case includes indirect energy because site energy alone disguises the carbon intensity of fuels. For example, HVAC accounted for 45 percent of global energy consumption in the Buildings sector in 2005 but only 34 percent of $CO_2$ emissions. This gap is due to the lower emissions intensity of direct fuels compared with electricity in many regions. In contrast, electricity-driven appliances and lighting account for a relatively large proportion of emissions due to the high amount of primary energy required for electricity generation (Exhibit 8.7.1).

**Exhibit 8.7.1**

**End-use energy consumption and emissions in the Buildings sector, 2005**




* Other includes cooking energy (such as stoves and small kitchen appliances), small devices (such as coolers and plug devices), and other mechanical / electrical equipment (such as elevators, escalators, and electronic key cards)
Source: Global GHG Abatement Cost Curve v2.0

65 Our growth assumption falls within IPCC range of scenarios for 2030, which project emissions ranging from 11.4 $GtCO_2e$ to 15.6 $GtCO_2e$ per year.

## Potential abatement

We have identified 26 options for abatement in the Buildings sector, which we can group in six categories (Exhibit 8.7.2):

A. **New building-efficiency packages (approximately 920 $MtCO_2e$ per year in 2030).** Efficiency packages for new residential, commercial, and public buildings can reduce demand for energy consumption through improved design and orientation that take advantage of passive solar energy. The model assumes aggressive abatement measures to reach passive housing standards. Building insulation and air-tightness can be improved through use of better materials and construction of walls, roofs, floors, and windows. Furthermore, the use of high-quality mechanical ventilation with heat recovery minimizes the need for heating and cooling and ensures a high level of air quality. The "new buildings package" also assumes the use of high-efficiency water-heating technology. A new building-efficiency package for residential buildings can achieve energy consumption levels comparable to passive housing, which reduces HVAC and water heating energy consumption by up to 70 percent in developed countries, reducing site energy consumption from 115 $kWh/m^2$ to around 35 $kWh/m^2$.

B. **Retrofit building envelope (about 740 $MtCO_2e$ per year).** For existing residential, commercial, and public buildings, retrofit measures focused on improving building air-tightness can achieve significant reductions in heating and cooling demand. In the residential segment, we have designated two retrofit packages that include moderately aggressive assumptions. A "Level 1" retrofit of residential buildings includes weather-stripping of doors and windows; improving the air seal around baseboards, ducts, and other areas of leakage; insulation of attic and wall cavities; and the installation of basic mechanical ventilation systems to ensure air quality. These measures reduce the global average of site HVAC consumption from 70 $kWh/m^2$ to 54 $kWh/m^2$. A "Level 2" residential retrofit package is a major upgrade that could be performed in conjunction with building renovations typically occurring every 30 years or so. The Level 2 retrofit includes retrofitting windows with triple-paned models and high-efficiency glazing; adding outer wall, roof, and floor insulation; ensuring mechanical ventilation with a high level of heat recovery; and taking advantage of passive solar opportunities when these are cost-effective. These measures can further reduce site HVAC consumption to around 25 $kWh/m^2$.

C. **HVAC for existing buildings (around 290 $MtCO_2e$ per year).** For existing residential, commercial, and public buildings, HVAC systems can be replaced with high-efficiency systems when existing systems are retired. Existing gas and oil heaters should be replaced with models exceeding AFUE ratings of 95, leading to savings of around 20 percent[66]. Similarly, air-conditioning (AC) units could be replaced with models rated 16 SEER or above.[67] In appropriate climates, electric furnaces can be replaced with high-efficiency electric heat pumps, which would yield savings of 35–50 percent, depending on the climate. Improved maintenance can reduce energy consumption from HVAC and AC systems (e.g., correct level of refrigerant, regularly replaced air filters, and improved duct insulation to reduce air leakage and proper channeling of heated and cooled air). Finally, HVAC control systems in commercial and public buildings can be improved to adjust for building occupancy and minimize recooling of air. Our model includes moderate assumptions without early retirement of HVAC systems and fuel switching.

D. **Water heating for existing buildings (around 350 $MtCO_2e$ per year).** For existing residential, commercial, and public buildings, water heating systems can be retrofitted with high-efficiency systems. Replacing gas water heaters upon expiration of existing units with tankless or condensing

66 AFUE is annual fuel-utilization efficiency.

67 SEER is seasonal energy-efficiency ratio.

heaters would reduce energy consumption by around 30 percent, and replacement with solar water heaters could achieve savings of between 75 and 85 percent. Replacing standard electric water heaters with heat pumps upon expiration of existing units could save around 60 percent of energy use, while switching to solar water heaters could save between 65 and 80 percent. Our model includes moderate abatement assumptions in this category, without early retirement of systems and only a moderate penetration of solar-power systems in developed countries due to their high cost.

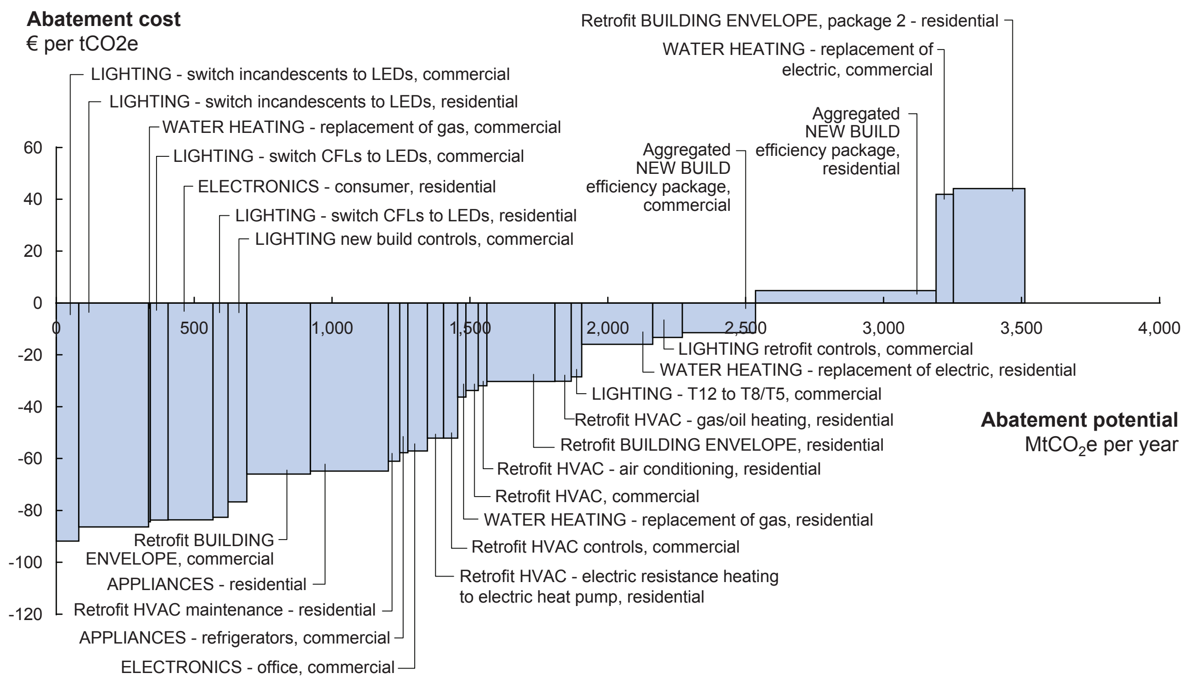
**E. Lighting (some 670 $MtCO_2e$ per year).** Existing incandescent and compact fluorescent lamp (CFL) bulbs in residential, commercial, and public buildings can be replaced with energy-efficient light-emitting diode (LED) bulbs. LEDs are estimated to provide 150 lumens per Watt (lm/Watt), compared with 60 lm/W for CFLs and 12 lm/W for incandescents.[68] In addition, existing T8 and T12 fluorescent tube bulbs in commercial and public buildings can be replaced with energy-efficient super T5s and super T8s. Lighting-control systems (controlling dimmable ballasts and photosensors to optimize light for room occupants) can be installed in new commercial and public buildings or retrofitted in existing buildings. Our model is aggressive for lighting levers, assuming nearly complete conversion to LEDs by 2030.

**F. Appliances and electronics (about 550 $MtCO_2e$ per year).** Energy-efficient electronics (e.g., consumer electronics and office electronics that reduce standby losses) can be purchased for residential, commercial, and public buildings. Energy-efficient residential appliances show 35 percent energy savings on average, with commercial refrigerators and freezers offering the potential of 15–20 percent savings. Our modelling assumptions are moderately aggressive for appliances, assuming a high level of decarbonization due to the high penetration of energy-efficient devices in the BAU case.

**Exhibit 8.7.2**

## Global GHG abatement cost curve for the Buildings sector

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

68 An 18 percent learning rate is assumed for LED bulbs. LEDs are expected to reach 75 lm/W by 2010 and 150 lm/W by 2015

Advanced computer programs for monitoring and controlling buildings' electricity usage could yield additional energy savings and emission reductions.[69]

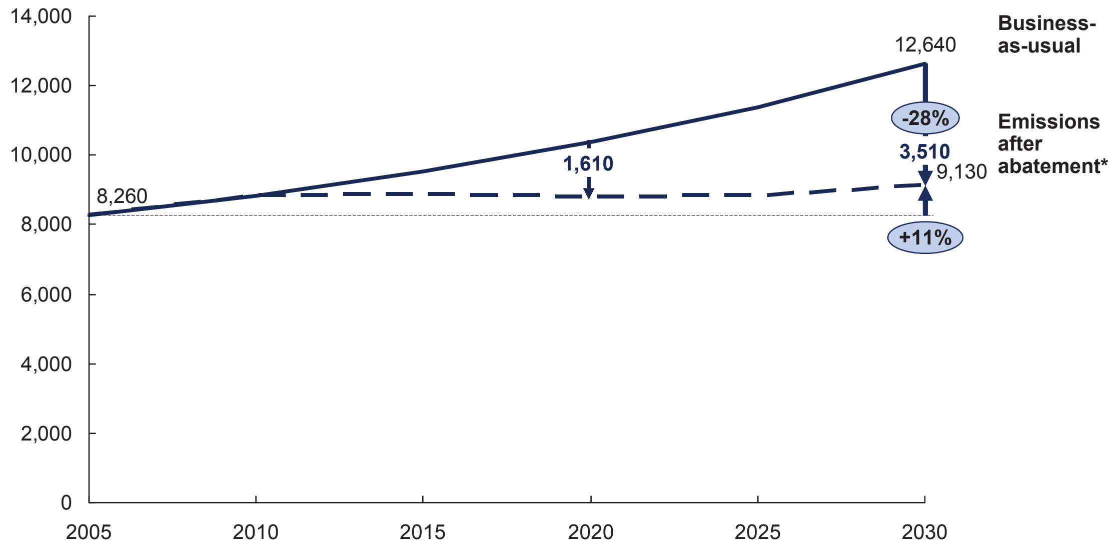
The abatement measures considered in this analysis do not assume lifestyle or behavior changes. Behavioral change from building occupants could reduce carbon emissions significantly beyond the abatement cost-curve model. The range of potential behavioral changes is broad, including reduced usage of hot water, lower home-heating temperatures, choosing homes closer to work, or even purchasing smaller homes. While behavioral changes are difficult to implement and monitor from a policy standpoint, such adjustments by building occupants could yield higher abatement potential, an issue that we address in chapter 3.

All major end-uses – HVAC, water heating, appliances, and lighting – have significant abatement potential. The residential segment provides at 2.4 $GtCO_2e$ per year twice as much total abatement opportunity as the commercial segment at 1.1 $GtCO_2e$ per year. This reflects the high proportion of emissions coming from the residential segment. The abatement potential of all levers grows consistently over time to 3.5 $GtCO_2e$ per year globally by 2030 (Exhibit 8.7.3), which results in emissions levels below the 2005 baseline in most developed countries.[70]

**Exhibit 8.7.3**

**Overview of emissions pathways for the Buildings sector**

$MtCO_2e$ per year




* Economic potential of technical measures

Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

Approximately 75 percent of the total abatement potential in the Buildings sector shows net economic benefits, with the remainder available at very low cost. Lighting options, particularly the introduction of LED bulbs, yield high net profits to society. The net economic benefits of the abatement potential in

69 These software applications are known as Energy Management Systems (EMS) and Building Management Systems (BMS).

70 The model does not include the abatement potential offered by cooking equipment and other very small appliances.

this sector overall is due to high energy savings over the full lifetime of investments. The average cost for the overall abatement potential is negative throughout the period of our analysis.

Despite the net economic benefits, new capital investments initially exceed immediate operational cost savings. Capital expenditures are projected to grow significantly through 2025 due to high requirements for purchasing initial goods. However, between 2026 and 2030, cost savings from energy efficiency will begin to outweigh new capital requirements. Operating expenditures will show immediate savings, which increase over time as energy-efficiency initiatives from earlier periods will continue to deliver energy savings.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | -21 | 124 | -24 |
| **2020** | -25 | 169 | -83 |
| **2025** | -28 | 187 | -156 |
| **2030** | -32 | 198 | -235 |

**Geographical differences.** Because of differences in climate and development levels, there is substantial variation in emissions (both current and predicted) across different geographies and regions in the Buildings sector, and therefore significant differences in opportunities for emissions abatement.

Developed countries can generally reduce energy consumption through retrofits of existing buildings and increased use of high-efficiency devices. Developing countries have an opportunity to design energy-efficient new construction, which is significant in light of building booms in several nations that are set to continue. China alone is expected to add nearly 2 billion square meters of floor space every year by 2020, and over 6 billion square meters of residential space in 2026–2030 – nearly six times the amount forecast for the United States in that period. In the United States, the relatively high cost of energy will improve the attractiveness of energy-efficient retrofits and new builds.

The abatement case shows a 25 percent reduction in emissions in China, compared with a 30 percent reduction in the United States. The two nations account for more than 40 percent of the total global abatement potential. However, even after abatement, China and the United States will remain the world’s top emitters. The average reduction across all countries and regions is 28 percent, with generally higher potential for emissions abatement in colder climates as well as in those areas that currently have high energy consumption per square meter.

## Implementation challenges

Much of the abatement potential in the Buildings sector would come from millions of small emitters, many of whom are individuals, rather than a limited number of large companies that are easier to influence and potentially to regulate. This fragmentation contributes to significant barriers to implementation of abatement levers:

- **Payback period.** Consumers have often been resistant to even small upfront costs, such as those required for energy-efficient appliances, if the payback period exceeds two years. Payback periods for more extensive retrofits, such as high-efficiency HVAC systems, are far longer.
- **Agency problems.** Incentives to improve buildings, whether through new builds or retrofits, are often misaligned. For example, building contractors typically will not build energy-efficient features into houses beyond minimum building-code requirements because buyers will be ultimately responsible for the operating costs of the buildings. Furthermore, builders are often constrained by upfront capital costs, which will affect a buyer's decision to purchase a building. Similarly, landlords have difficulty passing on costs of energy-efficiency improvements to tenants.
- **Visibility.** In many markets, customers do not see the real cost of power for heating, cooling, or electricity, which limits the potential for price signals to encourage changes in behavior.

These challenges have prevented energy-efficiency improvements to buildings in the past despite the high negative cost and ease of installation in many cases (e.g., lighting). Regulatory and market-based solutions are required to overcome the massive implementation challenges in the Buildings sector.[71] Technical norms and standards could be crucial in realizing the full abatement potential.

71 One example is Energy Saving Performance Contracts (ESPCs) in the United States, which help to address the upfront capital investments and monitoring issues in commercial buildings.

## 8.8 Waste

The Waste sector emitted 1.4 $GtCO_2e$ annually, or 3 percent of total global emissions in 2005. Without abatement measures, these emissions are projected to increase to 1.7 $GtCO_2e$ per year in 2030 as a result of an increased population and wealth worldwide. If captured, the full abatement potential in the sector would effectively eliminate waste emissions. About 60 percent of the abatement potential is achieved through recycling. While we account for this potential in the Waste sector, various industry sectors realize the abatement. The average cost for all abatement measures is negative at *minus* € 14 per $tCO_2e$, due to the avoidance of significant costs through the use of recycled goods in manufacturing processes and the use of mature, simple technologies for landfills. Achieving the potential abatement would require countries substantially to improve their recycling practices.

GHG emissions from waste derive mainly from solid waste and wastewater. Solid waste in landfills produces methane from the anaerobic decomposition of organic material. The main factors determining solid-waste emissions are the share of organic waste, the wetness of the system, weather conditions, and the design of the landfill. Wastewater produces methane through the anaerobic decomposition of the organic waste in the water. These emissions are particularly acute in developing countries that tend to have inadequate collection and treatment systems for wastewater. Another form of wastewater is sewage, which produces nitrous oxide ($N_2O$) from nitrogen. Industrial wastewater can also contain significant nitrogen loading.

Landfilling of solid waste and wastewater accounted for approximately 93 percent of waste emissions in 2005. Of this, 53 percent came from solid waste (totaling 750 $MtCO_2e$) and 40 percent from wastewater (560 $MtCO_2e$). Emissions from sewage account for the remaining 7 percent. All waste emissions are non-$CO_2$ in the form of methane and $N_2O$, both of which have much greater global warming potential than $CO_2$.[72] Landfill gas emits on average approximately 1 $tCO_2e$ per tonne of waste. Recycling and composting reduce the volume of solid waste that must be landfilled. Landfills are maintained according to regulations as the final disposal site of solid waste.

72 Methane's global warming potential (GWP) is about 21 times that of $CO_2$ over a 100-year period, while the GWP of $N_2O$ is about 296 times that of $CO_2$ over a 20-year period.

The scope of our waste analysis includes the pre-treatment (i.e., recycling and composting) and treatment (i.e., landfill-gas capture) of solid waste. Wastewater emissions abatement is not assessed due to lack of data. GHG emissions from the use of waste burned for energy are accounted for in the sectors using that waste, and emissions from waste collection are accounted for in the Transportation sector.[73]

## Business-as-usual emissions

The BAU case reflects emissions resulting from operations in waste disposal worldwide – i.e., in the absence of significant abatement efforts. In BAU, waste emissions will grow at 0.9 percent per year, reaching 1.7 $GtCO_2e$ per year in 2030, an overall increase of 24 percent in 2005–2030. Growth in the global population and in wealth drives this increase, offset by an expansion of covered landfills in developed countries.

In 2005, waste generation ranges from an estimated 100 kg of waste per capita in India to 225 kg in China, 550 kg in European Union countries, and about 750 kg in the United States.[74] In BAU 2030, developing Asia and Africa account for just over half of emissions, with the United States representing another 10 percent of emissions.

The BAU incorporates a significant degree of emissions abatement by 2030, because of the strict landfill regulations already in place in developed countries and the fact that landfill gas can be used for energy generation. Just over half of the global potential for abatement from recycling and composting is included in the BAU case, while the percentage of implementation for landfill-gas levers in the BAU ranges from 11 percent for flaring to 25 percent for electricity generated from landfill gas. The average degree of implementation for all abatement options in the BAU is already 50 percent in 2030.

The proportion of emissions from solid waste decreases slightly in the BAU case, from 53 percent in 2005 to 51 percent in 2030, while the proportion from wastewater increases respectively.

We draw the BAU primarily from US EPA data and analysis, with additional inputs from the IPCC.[75]

## Potential abatement

The abatement levers identified for the Waste sector can be aggregated into three groups (Exhibit 8.8.1):

A. **Existing waste.** The methane emitted by solid waste in landfills can be captured and used with a system of pipes and wells. Landfill gas then can be used to generate electricity, sold to a nearby industrial user, or burned (flared) to prevent methane from entering the atmosphere. It is technically difficult to collect all of the landfill gas produced and not all techniques can be applied at all landfills. The abatement case assumes that 75 percent of landfill gas can be captured over the lifetime of a landfill. Direct use of landfill gas is assumed to be limited to 30 percent of the

73 Incineration and gasification are excluded from this analysis. In many circumstances, these technologies could be useful in abating emissions.

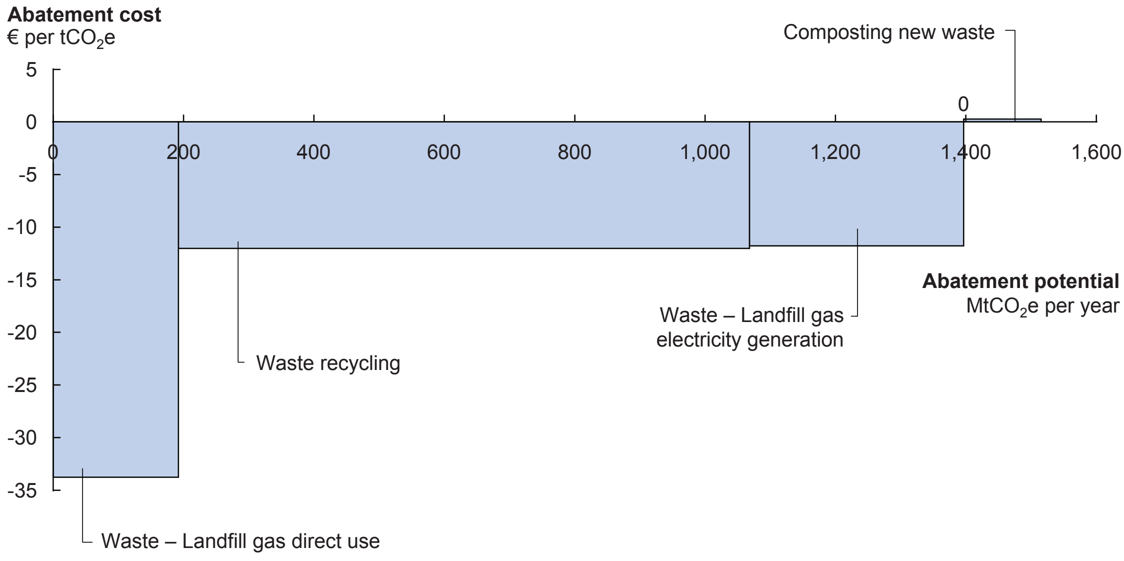
74 This is based on a UN database on waste generation by country.

75 McKinsey thanks the IPCC for contributing to the baseline data and the EPA for its collaboration.

**Exhibit 8.8.1**

## Global GHG abatement cost curve for the Waste sector

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

landfill sites, based on the availability of nearby industry that can leverage the energy. Electricity generation from landfill gas is assumed to be limited to 80 percent of the sites, based on the size of landfills where this option is economically attractive.[76] The abatement case assumes that any potential remaining site would apply landfill-gas flaring.[77] Taking the United States as an example, out of an estimated 1,800 landfills, landfill-gas levers would be implemented at about three-quarters in the reference case, with landfill gas captured at the remaining 450 landfills in the abatement case during 2010–2030. Direct use of landfill gas is highly net-profit-positive (€ -34 per $tCO_2e$) because of the savings from using it as a fuel for nearby industrial facilities. Similarly, landfill gas used to generate electricity also has a significantly negative cost.

**B.** **New waste.** Solid waste can be sorted for the recycling of glass, paper/cardboard, plastic, and metal waste, and the composting of organic waste. Recycling and composting reduce the introduction of new waste to landfills, thereby avoiding landfill and industry emissions. In recycling, energy savings from avoided production for new materials (e.g., metals and paper) drives emissions reductions. Recycling has a significant negative cost for the same reason. Recycling reduces emissions by 3.2 $tCO_2e$ to 5.1 $tCO_2e$ per tonne recycled, depending on the regional waste composition. Composting avoids methane emissions from new organic waste. Composting reduces emissions on average by 1.1 $tCO_2e$ per tonne composted. (The overall abatement potential from composting is small because the abatement is accounted for over 35 years.) Composting has a slightly positive cost to society. The abatement case assumes that about 10 percent of solid waste that could be recycled or composted is irrecoverable in developed countries; in developing countries, the figure is up to 15 percent. It is assumed that 100 percent of that recoverable waste

76 We base this on estimates from IPCC experts.

77 The three landfill-gas abatement levers apply to the same sites; overall implementation equals 100 percent with the combined measures. We base the volume of abatement for the three levers applied to landfills on a merit order logic in which the least-expensive lever in 2030 is implemented first.

is recycled and composted by 2030. For recycling only, globally about 440 million tonnes of waste would be processed in the BAU and another 310 million tonnes in the abatement case, giving a total of about 750 million tonnes of recycled waste.

**C. Wastewater.** Improved treatment of wastewater at current facilities (e.g., better filtering) can reduce emissions. Wastewater treatment facilities can be built in countries with no available facilities, i.e., mainly developing countries. However, given the lack of reliable data on wastewater abatement, we have not estimated the potential in this analysis.

The abatement potential for solid waste is estimated at 1.5 $GtCO_2e$ per year in 2030. Full abatement would reduce emissions to 0.2 $GtCO_2e$ per year, due to the effect of recycling reductions on energy efficiency in various industry sectors. Importantly, recycling abatement is accounted for in the Waste sector but is achieved in relevant industry sectors. Of the abatement potential, approximately 60 percent comes from recycling.

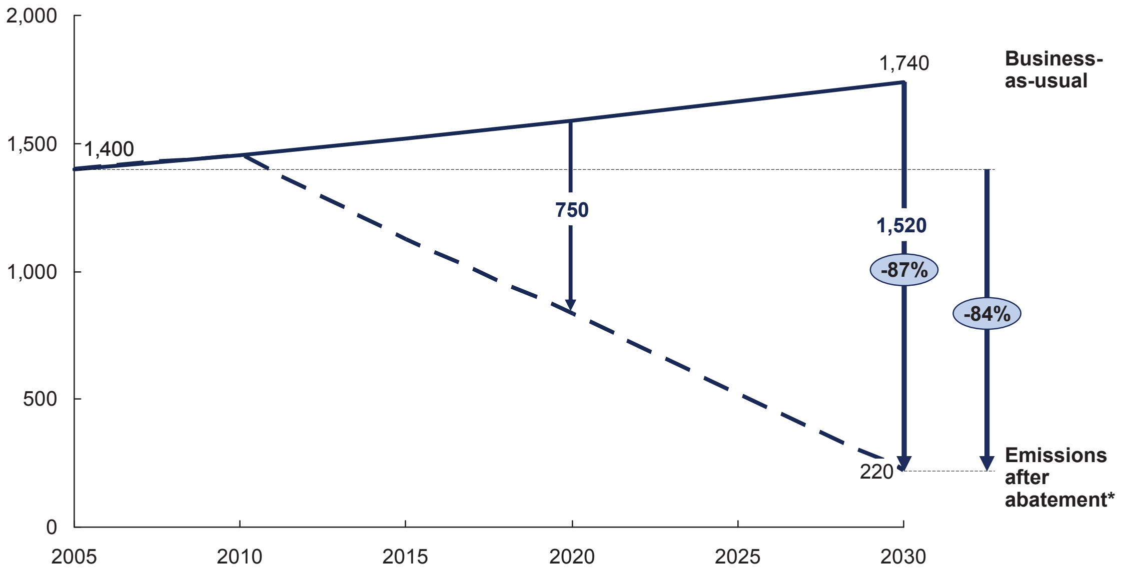
Asia and developing Africa account for 38 percent of the total abatement potential, The United States represents another 16 percent of abatement potential. India, which emits 9 percent of $CO_2e$ in the reference case, accounts for only 1.5 percent of the potential abatement due to a very low proportion of waste collection and a small share of metal in the composition of the country's waste (a component with relatively high abatement potential).

The potential abatement volume increases over time due to gradual implementation of the levers up to 2030 (Exhibit 8.8.2). The average degree of implementation for all waste-abatement options in the abatement case is about 85 percent in 2030 as a certain share of the waste is assumed to be impossible to collect and sort.

Exhibit 8.8.2

**Emissions development for the Waste sector**

$MtCO_2e$ per year




* Economic potential of technical measures

Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

Capital expenditures for waste emissions abatement total about € 210 billion for the full study period. However, operating expenditure savings of € -360 billion outweigh these investments, driven by high operating revenues (i.e., savings from avoided costs). In 2015 investments are still higher than savings and, beginning in 2020, society benefits financially as savings exceed new spending.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | -13 | 9 | -5 |
| **2020** | -13 | 14 | -14 |
| **2025** | -13 | 11 | -22 |
| **2030** | -14 | 8 | -30 |

## Implementation challenges

Educational programs to change individual practices, such as recycling and composting habits, and appropriate enforcement of policies will be required to achieve the waste-abatement potential.

Technical constraints (e.g., engineering capacity) will exist for the rollout of the different abatement techniques in some regions, particularly for landfill-gas use. However, we assume that these challenges are resolved by 2030. For example, Germany has achieved very significant reductions in solid waste. Total waste volume declined by 68 percent between 1990 and 2004 and related emissions dropped from about 36 $MtCO_2e$ to 11 $MtCO_2e$ in the same period. These reductions are expected to continue, reaching about 5 percent of 2005 emissions by 2020. The main drivers are regulations requiring the elimination of methane emissions from waste landfilled after 2005, through thermal or mechanical biological pre-treatment, and stringent guidelines to collect gases from residuary landfills. Germany has also expanded incineration using energy recovery (electricity and heat).

## 8.9 Forestry

Land use, land-use change, and forestry are the fourth-largest source of global greenhouse gas emissions, accounting for 16 percent of global GHG emissions, or 7.4 $GtCO_2e$ per year in 2005.[78] Forestry sector emissions occur mainly thorough the deforestation of tropical forests and the drainage and burning of tropical peatlands. In the absence of abatement measures, we expect Forestry sector emissions to remain substantially unaltered to 2030, reaching 7.2 $GtCO_2e$. The main means of abatement is avoiding deforestation, and the estimated abatement potential for the Forestry sector is very large. Most of the abatement potential is at very low cost. It is difficult to implement the abatement measures identified due to the diffuse nature of the opportunity, the fragmentation of the potential actors, the complexity of implementing effective land-use policies in developing countries, and the need for substantial capacity-building.

Forestry includes land use and land use change. The sector is one of the largest sources of emissions globally – and the second largest source in the developing world. Deforestation emissions account for 73 percent of the total, the rest being due to the drainage and burning of peatlands. Full 88 percent of deforestation emissions result from the deforestation of tropical forests, which occurs because of clearance for agriculture (although tropical forest soil tends to be poor in nutrients) and a lack of clear land ownership. Brazil and Indonesia each account for one-third (1.7 $GtCO_2e$ per year) of 2005 deforestation emissions, with Africa also contributing a significant share (0.9 $GtCO_2e$ per year, or 16 percent).

Forest ecosystems draw down atmospheric $CO_2$ through photosynthesis and store it in biomass and other carbon stocks. While mature or primary ecosystems are generally in carbon balance (i.e., photosynthesis equals respiration), in young forests photosynthesis exceeds respiration and additional carbon is stored in the ecosystems. In other words, new and young forests display negative $CO_2$ emissions, and deforested or unsustainably logged forests release positive emissions.

Emissions from land use change can be substantial when mature forests are impacted. Deforestation and unsustainable forest harvesting remove carbon stocks from the forests and release them in the

78 Excluding negative emissions from forest reqrowth in the northern hemisphere, and including emissions from peat drainage and fires; see section on BAU emissions below.

atmosphere. It is estimated that a single hectare of primary tropical forest can contain over 800 $tCO_2e$, nearly two-thirds in the form of above-ground biomass.

Conversion of tropical forest to palm-oil plantation can reduce carbon storage by two-thirds.[79] In 1980–2005, global deforestation removed 332 million hectares of forest – an area the size of India – with estimated cumulative emissions of 138 $GtCO_2e$.[80] The timing of carbon release from deforestation depends on many factors, including the mix of end-uses of the removed wood, the fate of the biomass and wood left on site, and the level of soil disturbance. These factors present potential levers for emissions abatement.

Reducing emissions from deforestation and forest degradation (REDD) is therefore a substantial opportunity for meeting GHG emissions reduction targets. Afforestation, reforestation, and forest management can also contribute to the reduction of GHG through the sequestration of $CO_2$ from the atmosphere into terrestrial carbon pools.

Although there is substantial consensus on the basic mechanisms of forest-based mitigation, large discrepancies still exist in the scientific community on the size and cost of the opportunity, as well as on the regulatory mechanisms that can be used to capture it. However, the majority of expert forecasts concur in showing a slight decrease in overall forest-based carbon emissions in the future.

The discrepancies are driven by basic uncertainty on actual deforestation rates (both current and future), on the carbon content of the deforested areas, on the rate of carbon loss from deforested areas (both past and current), and on the rate of re-growth of deforested and abandoned areas (both past and current), with different sources reporting base-case deforestation emissions ranging from 3 $GtCO_2e$ per year to more than 8 $GtCO_2e$ annually.

There is also uncertainty about the cost of implementing mitigation levers, mostly due to a lack of substantial experience in implementing the levers. The Kyoto Protocol mechanisms left out forest-based mitigation; as a consequence, until recently there has been limited experience of carbon-based afforestation and reforestation projects, and almost no experience with avoided deforestation. Most published estimates are based therefore on limited empirical evidence.

## Business-as-usual emissions

Global deforestation emissions were estimated at 5.4 $GtCO_2e$ per year in 2005. This excludes the negative emissions (i.e., sequestration) from the Forestry sector reported by several industrialized countries. (The largest carbon-emitting nations, including the United States and OECD Europe, are in fact carbon sinks for land use and forestry, while the key sources of carbon emissions are tropical regions.) Peatland and drainage emissions have been estimated to be 2.0 $GtCO_2e$ per year on average over the last decade – 0.6 $GtCO_2e$ per year from decomposition and 1.4 $GtCO_2e$ per year from fires.[81] Following the IPCC'S Fourth Assessment Report, Working Group III, we have included these emissions in our BAU case. Given the high interannual variability in fire emissions and basic uncertainty on the future rate of peatland fires, we have maintained these emissions constant through the study period.

79 FAO data for Democratic Republic of Congo; team analysis based on palm oil plantations in Indonesia.

80 We base this on Houghton estimates of annual emissions from tropical forests in 1980–2005.

81 A. Hooijer, M. Silvius, H. Wösten, and S. Page, PEAT-$CO_2$, Assessment of $CO_2$ emissions from drained peatlands in SE Asia, WL Delft Hydraulics and Alterra Wageninger UR, Q3943, 2006.

The BAU case assumes that deforestation will continue at a pace consistent with historical levels – 13 million hectares per year (with deforestation rates of 3.1 million hectares per year in Brazil and 1.8 million hectares per year in Indonesia), corresponding to 0.32 percent of the remaining forest area globally.[82] Deforestation will remain constant globally through 2030 in the BAU, with the exception of a few African countries, where deforestation is assumed to stop when the total forested area reaches 15 percent of the land base.[83] Thus, total emissions from tropical regions are forecast to decline slightly. Developed country emissions or sequestration are assumed to remain at the 2000–2005 average through 2030. In sum, overall emissions in the BAU case are forecast to decline by 3 percent until 2030. There is substantial uncertainty around these baseline emissions, however, because of the uncertainty about the level of past deforestation. Overall, an uncertainty of plus or minus 2 $GtCO_2e$ per year is a reasonable estimate.[84]

## Potential abatement

We have identified eight abatement levers in the Forestry sector, grouped into four categories:

1. **Avoided deforestation (REDD) (about 65 percent of total potential abatement, 5.1 $GtCO_2e$ per year in 2030).** REDD strategies seek to prevent emissions of terrestrial $CO_2$ by avoiding a net decrease in forest area or volume. REDD is pursued mostly by social and public-sector stakeholders (e.g., governments, NGOs, and charitable foundations). REDD requires an implementation strategy beyond the project base because of the risk of leakage – i.e., deforestation avoided in one area that causes an increase in deforestation in other areas. REDD measures are not currently integrated within existing compliance markets, although projects have been initiated to generate carbon credits for the voluntary markets. Our volume estimates are based on stopping all deforestation in Asia and Latin America and preventing 70 percent of deforestation in Africa by 2025, based on research indicating that a full cessation of deforestation in the Brazilian Amazon would be feasible within ten years.[85] Our estimates of the mitigation cost and volume from avoided deforestation are based on the following approaches:
   a. To reduce slash-and-burn and other forms of subsistence agriculture; compensation payments and income support to the rural poor and forest people;[86]
   b. To reduce conversion to pastureland and cattle ranching; compensation to landholders for the lost revenue from one-time timber extraction and future cash flow from ranching;[87]

82 Country-level figures are as reported by FAO Forest Resource Assessment 2005 for 2000–2005, which includes both Amazon deforestation, and deforestation in Cerrado and Mata Atlantica. According to INPE, the deforestation rate in the Brazilian Amazon was 2.2 million hectares per year for 2000–2005, declining to 1.2 million hectares a year in 2007.

83 We base deforestation emissions on Houghton's model estimates for tropical regions, and on UNFCCC estimates for developed regions. Houghton's model is based on deforestation rates contained in the FAO's Forest resource Assessment 2005, and reference carbon density. As such, it does not include the specific impact of peat decomposition or peat fires. A minimum limit of residual forest area of 15 percent follows Houghton's assumptions and, although somewhat arbitrary, it is not material to the BAU case, impacting only 5 percent of the emissions before the effect of sinks, very small when compared with the basic uncertainty around LULUCF emissions.

84 Estimates of deforestation in the pan-tropics based on remote sensing have been consistently lower than the rates reported by the FAO Forest Resource Assessment. Both the FAO and remote sensing studies are methodologically unable to capture the effect of land degradation and emissions from tropical peatlands.

85 Research conducted by Woods Hole Research Center.

86 Assuming payments of $1,200 annually to Brazilian households, with payments in other regions scaled to the annual income of the poorest 20 percent of the population.

87 Ranching profits are $15/hectare annually in Brazil. Timber extraction is calculated at 70 percent of standing merchantable volume.

c. To reduce conversion to intensive agriculture; compensation to landholders for the lost revenue from one-time timber extraction and future cash flow from agriculture;[88]

d. To reduce unsustainable timber extraction; compensation to landholders for lost timber revenue.[89]

2. **Afforestation of marginal pasturelands and croplands (around 13 percent of total potential abatement, 1.0 $GtCO_2e$ per year in 2030).** Afforestation is the plantation of forest carbon sinks over marginal pastureland and marginal cropland, and is a method of incremental biosequestration of $CO_2$. Carbon is sequestered in forest carbon pools. Because of the project-based approach of afforestation, private-sector stakeholders (e.g., corporations and asset managers) play an important role. Afforestation is partially integrated in existing compliance markets.[90] The estimated potential implies an incremental afforestation of 92 million hectares in 20 years, or 4.6 million hectares per year—an area larger than Denmark. The afforestation potential depends on the quantity of available marginal cropland and pastureland, which is limited by the need to supply food and feed to a growing population. We account for this limitation in the stated potential.

3. **Reforestation of degraded lands (about 18 percent of total potential abatement, 1.4 $GtCO_2e$ per year in 2030).** Reforestation of degraded lands is the plantation of forest carbon sinks over degraded land with no food or feed production value. We base our estimates of afforestation and reforestation mitigation potential and costs on a "carbon graveyard" forest case in which forests are not harvested. Reforestation projects are similar to afforestation. The two mitigation approaches are jointly referred to as A/R.[91] The estimated potential implies an incremental reforestation of 238 million hectares in 20 years, or 11.9 million hectares per year—about twice the size of Croatia. While the reforestation potential is limited in a few regions by the amount of available degraded lands, in most regions it is the estimated maximum annual reforestation rate.

4. **Forest management measures (about 4 percent of total potential abatement, 0.3 $GtCO_2e$ per year in 2030).** Forest management is the increase of the carbon stock of existing forests based on active or passive management options such as fertilization, fencing to restrict grazing, fire suppression, and improved forest regeneration. Thus, forest management is a method of incremental biosequestration of $CO_2$. Private-sector stakeholders play an important role in forest management because of the project-based approach to creating a net increase of standing stock. Most forest management measures are not integrated within existing compliance markets. The estimated potential is based on applying forest-management measures to the global forest area, including temperate and boreal forests, at a rate that is feasible for the forests of the United States.[92] While covering a very large area, the total abatement potential of forest management is limited by timber production and harvesting; i.e., they are purely efficiency improvements in managed forests.

REDD dominates the potential abatement of emissions, followed by A/R, with limited opportunities in forest management (Exhibit 8.9.1).

88 Reference crops are soybeans for South America and palm oil for Asia and Africa. Timber extraction is calculated at 100 percent of standing merchantable volume.

89 Timber extraction is calculated at 15 percent of standing merchantable volume.

90 Annual rental for crop and pasture lands is based on regional averages. One-time capital investment and annual management costs are based on US estimates. Payments are matched to carbon flux, assuming full repayment of capital investment and present value of annual expenditures over 50 years of constant sequestration.

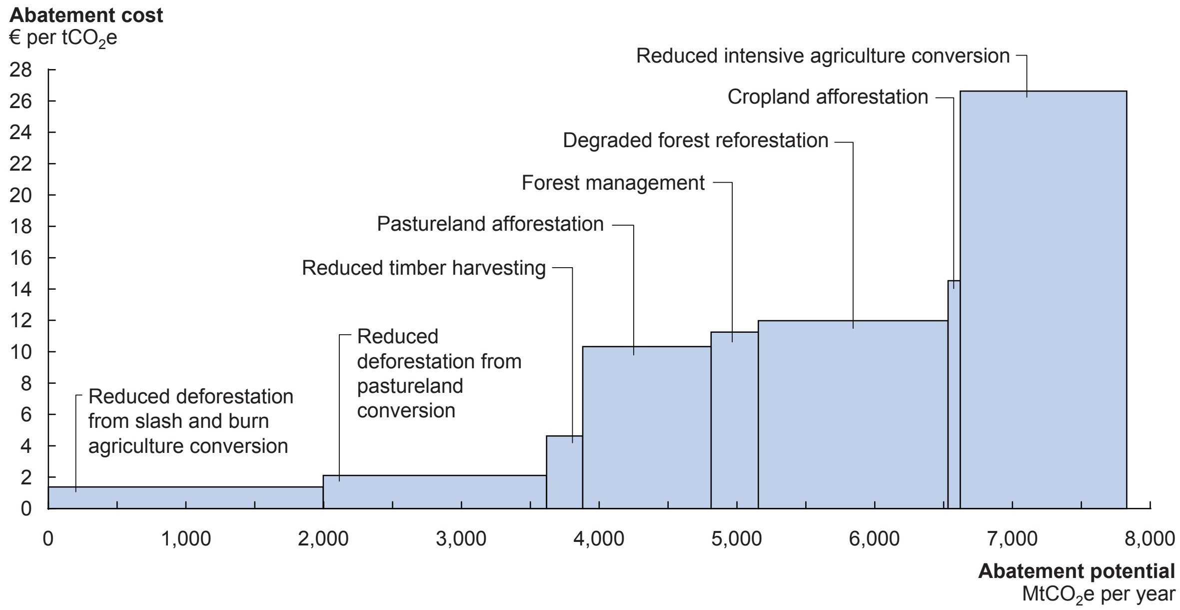
91 One-time capital investment and annual management costs are based on US and IPCC estimates.

92 Estimate by the US Forest Service.

Exhibit 8.9.1

## Global GHG abatement cost curve for the Forestry sector

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

The study reveals three key observations:

- A large, low-cost amount of potential abatement from REDD (3.6 $GtCO_2e$ per year) derives from activities that yield little economic value, including slash-and-burn agriculture and conversion to pasture;
- A/R is generally less expensive than avoiding conversion of forests to high revenue-intensive agricultural options;
- Afforestation of marginal croplands has very limited potential due to competition with food, feed, and bioenergy demands.

In sum, the estimated abatement potential by 2030 for land use, land-use change, and forestry is very large, and most of the potential is at very low cost. Abatement in this sector could reduce total emissions to *negative* 0.7 $GtCO_2e$ per year in 2030 due to creating carbon sinks. This is an abatement of 7.8 $GtCO_2e$ per year compared with the BAU case, which corresponds to a 109 percent reduction in BAU emissions in 2030 (Exhibit 8.9.2).

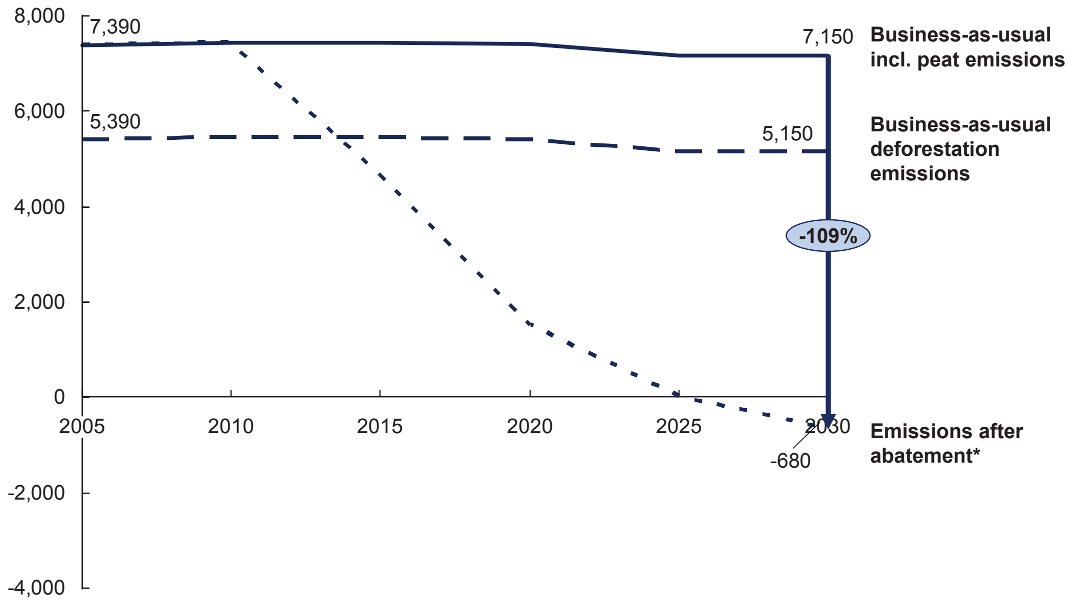
Nearly two-thirds of the overall abatement potential is based on mitigation of emissions of terrestrial carbon from deforestation activities, while the remaining 35 percent is based on offsets; i.e., on the absorption of $CO_2$ into terrestrial carbon pools.

The costs for forest-based abatement are relatively low. Nearly the entire potential identified would cost below € 30 per $tCO_2e$. In particular, avoided deforestation from slash-and-burn agriculture, and avoided deforestation from cattle ranching, offer high potential abatement at a very low average cost

**Exhibit 8.9.2**

## Emissions development for the Forestry sector

$MtCO_2e$ per year




* Economic potential of technical measures

Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

of below € 2 per $tCO_2e$. We did not identify any net profit-positive potential in the forest sector – both avoided deforestation and the creation of incremental offsets compared with the baseline involve economic costs.

| **Socioeconomic view** | **Average cost** (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | 9 | 15 | 1 |
| **2020** | 9 | 31 | 2 |
| **2025** | 9 | 41 | 2 |
| **2030** | 9 | 43 | 3 |

There is broad agreement that forest-based mitigation is large and inexpensive, but estimates of size and cost are very uncertain. While the cost of abatement measures is not expected to increase through 2030, it should be noted that abatement-cost forecasts are based on current agricultural commodity and land rental prices. A steep increase in commodity prices or land rents would lift the abatement cost. All cost estimates are highly dependent on which mechanisms were implemented to pursue forest-carbon mitigation – e.g., national funds versus market-based solutions.

While these costs include ongoing the monitoring and management of preserved forests, they do not include transaction costs, the cost of building new infrastructure, or the capacity-building cost necessary to set up the monitoring and management infrastructure, which itself could account for a reasonably large portion of the total cost in tropical countries. Also, the costs of avoiding leakage and insuring the permanence of carbon stocks against natural disturbance events are not included.

The annual cash flow needed during 2010 to 2030 equals about 35 percent of the total value of the global timber industry. The capital expenditures during this period are equivalent to 20 times current foreign aid to the agriculture and forestry sectors globally.

Abatement cash flow is dominated by the investment in REDD, accounting for about 80 percent of the total in 2030.[93] We have also treated Initial investments in A/R as capital expenditures in this study. Part of the REDD investment potentially could be shifted by converting it from a one-time investment to annual payments, although the specifics would depend on the REDD mechanisms adopted.

**Geographical differences.** The great majority – 88 percent – of the overall abatement potential comes from tropical regions, all of which are located in the developing world. REDD opportunities are concentrated in Latin America, developing nations in Asia, and Africa. Opportunities for A/R and forest management can be found globally, but the bulk is again concentrated in the developing world.

Low-cost options for REDD are present in all tropical regions, while higher-cost options are found mostly in Africa and developing nations in Asia. Currently, slash-and-burn agriculture – whose mitigation is very inexpensive – accounts for a large percentage of deforestation emissions from Africa (53 percent), Asia (44 percent), and Latin America (31 percent). Pastureland and cattle ranching, which are also cheap mitigation options, account for the majority of deforestation emissions from Latin America (65 percent) but a much lesser proportion of emissions from Asia (6 percent) and Africa (1 percent). Timber extraction – which is more expensive to mitigate than the previous two categories but still relatively low cost – accounts for a small proportion of emissions from Africa (10 percent), Asia (6 percent), and Latin America (3 percent). Finally, intensive agriculture – the most expensive abatement lever in this sector at € 27 per $tCO_2e$ – accounts for 44 percent of emissions in Asia, 35 percent in Africa, and only 1 percent in Latin America.

## Implementation challenges

Practical, political, and ethical reasons are likely to disconnect compensation to potential deforesters from the opportunity cost. For example, transfers to forest people or the landless poor might need to exceed opportunity costs substantially, and illegal logging or conversion to pasture might not be compensated at all.

A "payment for ecosystems services" approach, in which landholders are compensated for avoiding deforestation, could have very high inefficiencies; i.e., compensation is likely to go to some who would have not deforested in any case, increasing payment by a factor of between 2 times and 100 times. These payments would be transfers and not true economic costs to global economies, but would generate a certain amount of true costs related to an increased administrative burden, and could therefore inflate the budget of an avoided deforestation scheme when compared with the costs reported here.

National infrastructure and capacity-building costs are almost never accounted for in published cost estimates. These values are dependent on current institutional capacities, which are highly variable between high deforestation countries, and the implementation approaches taken.

93 The investment in REDD is assumed to be fully capitalized upfront; i.e., full capitalization of future liabilities for avoided deforestation support programs.

## 8.10 Agriculture

Agriculture accounts for about 14 percent of global GHG emissions, or 6.2 $GtCO_2e$ per year in 2005. Developing regions represent the largest share of these emissions, with Asia, Latin America, and Africa generating almost 80 percent of the total. About 70 percent of total emissions come from agricultural soil practices and enteric fermentation in livestock. In the absence of abatement measures, worldwide agricultural emissions are projected to grow by approximately 1.0 percent annually to about 8 $GtCO_2e$ per year, driven by increased population and meat consumption. The abatement potential in the Agriculture sector is very large at 4.6 $GtCO_2e$ per year identified by 2030, which is a little more than half of the emissions in the reference case. Three-quarters of the abatement potential is through carbon sequestration in soils. Most of the abatement levers come at a neutral cost or are net-profit-positive to society and require no substantial capital investment. However, we cannot understate the implementation challenges given the large complications caused by the high degree of fragmentation in agriculture in most parts of the world, especially in developing countries. The uncertainty around the abatement potential is significant, making the monitoring and the accounting of the measures even more challenging. Finally, most of the sequestration measures are estimated to be active for 20 to 40 years, which means that other levers will need to be phased in to replace these after 2030–2050.

Agriculture is comparable to the Road Transport and Forestry sectors in terms of the size of the sector's global emissions. Rather than carbon dioxide, agricultural emissions are in the form of nitrous oxide ($N_2O$) (46 percent of sector emissions) and methane (54 percent),[94] although the fact remains that carbon sequestration has a very large potential for GHG abatement in agriculture. We can divide emissions into five categories:

- **Agricultural soils** (nitrous oxide) – representing 37 percent of sector emissions (2.3 $GtCO_2e$ per year) as of 2005;
- **Livestock enteric fermentation** (methane) – 31 percent (1.9 $GtCO_2e$ per year);
- **Rice cultivation** (methane) – 13 percent (0.9 $GtCO_2e$ per year);
- **Livestock manure management** (methane and nitrous oxide) – 7 percent (0.4 $GtCO_2e$ per year);
- **Other agricultural practices**, such as open burning during agricultural activities (nitrous oxide and methane) – 12 percent (0.7 $GtCO_2e$ per year).

94 $CO_2$ releases from the conversion of forests to agricultural production are allocated to the Forestry sector in this analysis.

Agriculture is a very diverse sector; crop and livestock practices range from subsistence farming to intensive and industrial agriculture. In most countries, agriculture is a key national industry. The sector is highly fragmented, particularly in developing countries where a large percentage of the abatement potential is located. Farmers are believed to represent about 35 percent of the global workforce in 2007 or approximately 1 billion workers. Agricultural consumption increases with increased population and increased wealth. China accounted for 20 percent of Agriculture-sector emissions in 2005, Latin America 19 percent, and Africa 16 percent. Together, Asia, Latin America, and Africa create 76 percent of agricultural emissions. This analysis encompasses the production of agricultural commodities, including crops and horticultural products, and livestock. However, we exclude the distribution of agricultural products and processing/ manufacturing, which other sectors capture.

## Business-as-usual emissions

Without abatement measures, agricultural emissions are forecast to climb steadily from 6.2 Gt$CO_2$e in 2005 to 8.2 Gt$CO_2$e per year in 2030 – a growth rate of 1.1 percent per year or 31 percent increase in emissions over the whole period from 2005 to 2030. Three factors drive this increase: worldwide population growth (25 percent from 2005–2030); global development resulting in increased per capita GDP; and an expected worldwide shift in nutrition intake toward meat. The BAU case does not account for the consequences that climate change might have on agriculture (e.g., changes in rainfall and growing patterns), as the implications are unclear both in terms of the magnitude of the impact and the positive and negative aspects for different regions. The reference case includes the effect of carbon sequestration, which is estimated to bring GHG emissions down to 7.9 Gt$CO_2$e from 8.2 Gt$CO_2$e per year in 2030.[95]

The share of emissions from developing countries is expected to increase over time as a result of increasing population and GDP growth. Asia, Latin America, and Africa are projected to represent 79 percent of agricultural emissions in 2030 in the reference case (up from 76 percent in 2005).

We base the reference case on data from the US Environmental Protection Agency (EPA), the UN Food and Agriculture Organization (FAO), and the Intergovernmental Panel on Climate Change (IPCC). The US EPA baseline is widely recognized as the most accurate description of GHG emissions in agriculture.[96]

## Potential abatement

The identified abatement measures for the Agriculture sector have a total potential of 4.6 Gt$CO_2$e per year worldwide by 2030, equivalent to nearly 60 percent of emissions (compared with the BAU case). The abatement case is some 50 percent lower than 2005 emissions. It is important to note that the uncertainty around the abatement potential is significant and will be dependent on the geographies and climate.[97]

We have modeled 11 abatement levers for the Agriculture sector, which we can aggregate into four categories (Exhibit 8.10.1):

95 The EPA baseline excludes carbon sequestration levers.

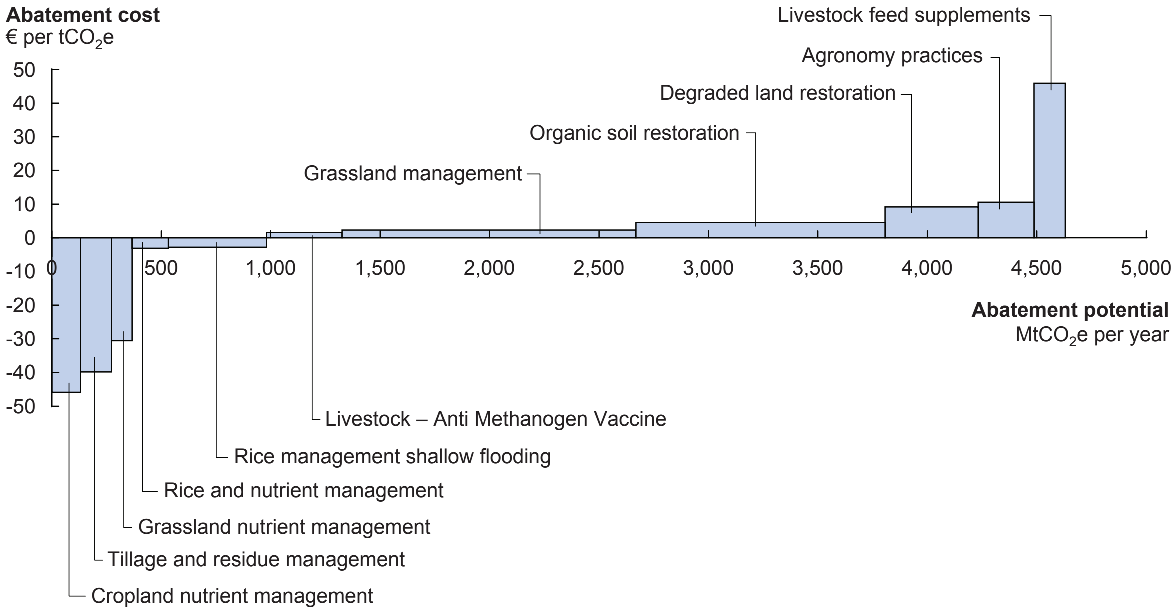
96 Global Mitigation of Non-$CO_2$ Greenhouse Gases, EPA, June 2006, has been used to define the baseline scenario through 2030.

97 Abatement figures are averages, which reflect higher reduction potential for some areas and lower or even potentially negative abatement (i.e., an increase in emissions) for other areas.

**Exhibit 8.10.1**

**Global GHG abatement cost curve for the Agriculture sector**

Societal perspective; 2030




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

**A. Pastureland (29 percent of abatement potential, 1.3 $GtCO_2e$ per year by 2030).** Improved grassland management is the single largest abatement lever, which consists of increased grazing intensity, increased productivity, irrigation of grasslands, fire management, and species introduction. Pastureland management can include the use of perennial and semi-perennial grasses as energy crops, which in turn can increase agricultural productivity. In addition, grassland nutrient-management practices can be improved through more accurate nutrient additions and better fertilization. Average abatement from this lever is around 0.4 $tCO_2e$ per hectare out of a global total of about 3,250 million hectares of pastureland.

**B. Land restoration (34 percent of abatement potential, 1.6 $GtCO_2e$ per year by 2030).** Land degraded by excessive disturbance, erosion, organic matter loss, acidification, for instance, can be restored through revegetation, improved fertility, reduced tillage, and water conservation.[98] Reestablishing a high water table for organic soils in order to avoid decomposition is a large abatement lever.[99] Reaching the full annual 1.1 $GtCO_2e$ per year of abatement in organic soils requires 1.1 million hectares of land being restored annually between 2020 and 2030, an area almost the size of Northern Ireland. Restoration of degraded land has a potential of 0.5 $GtCO_2e$ per year and but would require a much higher amount of land restored of 6.1 million hectares annually.

**C. Cropland management (27 percent of abatement potential, 1.2 $GtCO_2e$ per year by 2030).** Management of cropland to reduce GHG emissions consists of improved agronomy practices (such as improved crop rotations, less-intensive cropping systems, and extended use of cover crops), reduced tillage of the soil, reduced residue removal (from burning, for instance), improved

98 Land restoration does not include reforestation measures, which are accounted for in the Forestry sector.

99 Organic or peaty soils contain high densities of carbon accumulated over many centuries because decomposition is suppressed by absence of oxygen under flooded conditions. To be used for agriculture, these soils are drained, which aerates the soil, favoring decomposition and creating high $CO_2$ and $N_2O$ fluxes. Draining organic soils usually suppresses methane emissions, but this effect is far outweighed by pronounced increases in $N_2O$ and $CO_2$.

nutrient management (such as slow-release fertilizer forms, nitrification inhibitors, and improved application rates and timing), and better rice management and rice-nutrient management practices (such as mid-season and shallow-flooding drainage to avoid anaerobic conditions, and use of sulfate fertilizer instead of traditional nitrogen fertilizer). Rice practices, which are mostly limited to developing Asia, are the largest single lever in this category.[100] Average abatement from cropland management is around 0.7 $tCO_2e$ per hectare from the global total of about 1,750 million hectares of cropland.

D. **Livestock management (10 percent of abatement potential, 0.5 $GtCO_2e$ per year by 2030).** Dietary additives and feed supplements can reduce methane emissions from livestock. Livestock account for about one-third of global methane emissions. Additives that are currently available are relatively expensive but vaccines against methanogenic bacteria are being developed. This 0.5 $GtCO_2e$ per year corresponds to a 19 percent reduction in livestock emissions.

Although agricultural emissions today consist primarily of non-$CO_2$ GHGs, nearly three-quarters of the abatement potential is related to $CO_2$ through the avoidance of the release of carbon from soils or through additional carbon sequestration into soils.

Carbon sequestration levers include reduced tillage, grassland management, and degraded land restoration.[101] Organic-soils restoration accounts for one-third of carbon sequestration – and alone represents one-quarter of the total abatement potential in the Agriculture sector – as this effectively both stops the release of the carbon stock to the atmosphere and allows further build-up of carbon in the soil. Although there are only 25.2 million hectares worldwide of organic soils – 0.5 percent of total agricultural land – these soils have very high abatement potential per hectare.[102]

Organic-soils restoration often requires a switch from cropland back to swamps or peat soils, which implies a shift of food production to other areas. The impact of this shift can be very significant for countries and regions dominated by organic soils, such as Scandinavia and some Southeast Asian nations. This approach might meet resistance in favor of local food production, and therefore implementation of this lever might be limited in practice. On the other hand, global trade could make up for losses in local food production. For these reasons, the cost curve assumes implementation of organic soils restoration at 90 percent of the potential.

Nearly 90 percent of total abatement comes from measures related to soils.[103] After full abatement, emissions from soil would decline to 0.5 $GtCO_2e$ per year in 2030. Emissions from livestock increase slightly in the abatement case compared with 2005 to 2.7 $GtCO_2e$ per year in 2030.

Cropland and pastureland improvements correspond to a decrease in emissions from around 0.8 $tCO_2e$ per hectare of land in 2005 to about 0.3 $tCO_2e$ per hectare in 2030, an improvement of some 65 percent.

In sum, the estimated abatement potential by 2030 for agriculture is large relative to emissions, and most of the potential would come at a low cost (Exhibit 8.10.2). However, carbon sequestration declines in potential after 20 to 40 years as soils build up to their maximum carbon potential.

100 China already uses mid-season drainage in 80 percent of applications.

101 Other levers such as nutrient management can, in addition to reducing nitrous oxide emissions, also have a positive impact on the sequestration of carbon.

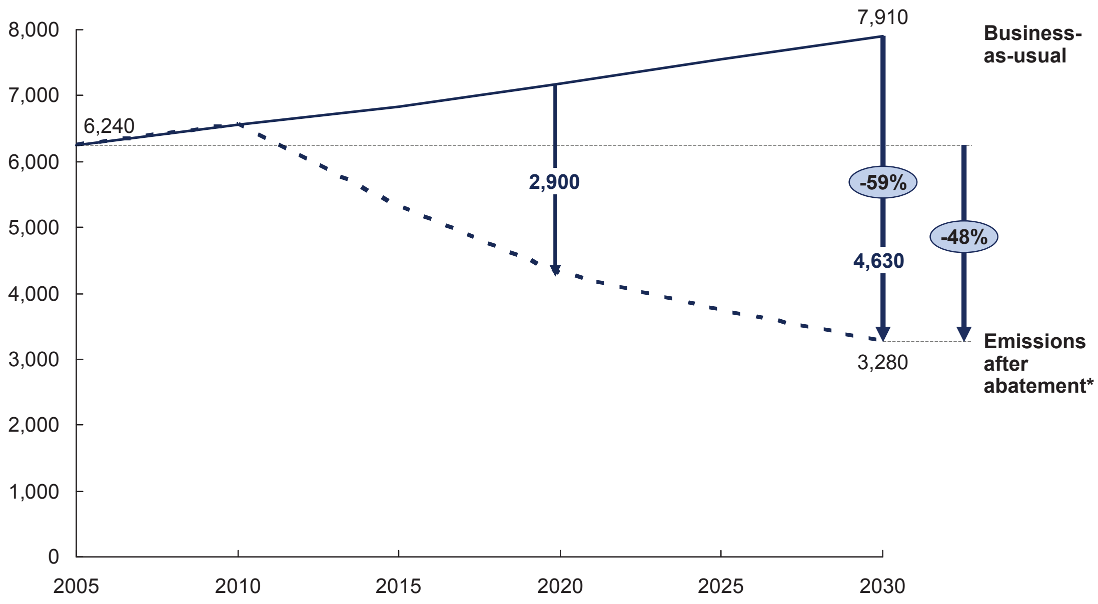
102 Organic or peaty soils contain high densities of carbon accumulated over many centuries because decomposition is suppressed by an absence of oxygen under flooded conditions as well as by soil build-up.

103 The volume of abatement for the levers on soils is based on potential per hectare estimated by the IPCC.

**Exhibit 8.10.2**

**Emissions development for the Agriculture sector**

$MtCO_2e$ per year




* Economic potential of technical measures

Note: This is an estimate of maximum economic potential of technical levers below € 60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

Furthermore, for most of the levers involved in carbon sequestration, a return to previous agricultural practices including high tillage levels would not only immediately stop the intake of carbon but also return the sequestered $CO_2$ to the atmosphere.

The average cost of abatement for all measures is very low, at around € 1 per $tCO_2e$ in 2030 and, within this average, most measures would be very inexpensive as they are assumed to imply small changes in agricultural practices and no significant capital investments. Soil restoration requires significant implementation and opportunity costs, but these are balanced by a large $CO_2$-abatement potential per hectare. For example, for organic soils, the implementation costs are about € 227 per hectare and the potential estimated at between 30 $tCO_2e$ and 70 $tCO_2e$ per hectare. Nutrient management is highly net-profit-positive on average, due to a reduction in fertilizer use. Tillage management also is net-profit-positive to society, since an increase in yield leads to a reduction in labor costs. Negative measures represent about 20 percent of the abatement potential. At the other end of the cost range, livestock feed supplements have a relatively high cost of abatement, since high doses are required per animal to achieve the abatement.

These cost calculations exclude program and transaction costs for two reasons. First, there are different routes to implementation, which have extremely different financial implications (e.g., through subsidies or taxes). Second, if implementation is accomplished through training programs and subsidies, exact costs are very hard to estimate. We investigated three categories of implementation costs: measurement and monitoring (estimated at € 0.2 per $tCO_2e$), capacity and infrastructure building (€ 0.7 per $tCO_2e$), and carbon-credit-monetization costs (€ 0.2 per $tCO_2e$). These categories add up to an estimate of € 1.1 per $tCO_2e$ (in line with data from external sources), leading to a total implementation cost of about € 3.8 billion for the Agriculture sector in 2030. However, uncertainty is high (by a factor of two to three times) in all such cost estimates. Further investigation is warranted, given the magnitude of the implementation costs and the high uncertainty level of current best estimates.

| **Socioeconomic view** | **Average cost**[64] (€ per $tCO_2e$) | **CapEx** (€ billion per year) | **OpEx** (€ billion per year) |
|---|---|---|---|
| **2015** | -0.5 | 0 | -0.5 |
| **2020** | -0.5 | 0 | -1.1 |
| **2025** | 0.5 | 0 | 0.3 |
| **2030** | 1.2 | 0 | 3.8 |

The total expenditures for all abatement levers over 2010–2030 is € 13 billion and increase over this period as abatement levers are implemented, whether in terms of land or livestock, incurring costs (of savings) each year. Levers are assumed to not require any substantial capital investment; the cash flow required is for operational expenditures only.

## Implementation challenges

The sheer size of land areas around the world and the number of farmers involved in measures such as reduced tillage or grassland management implies massive implementation challenges for all countries in abating GHG emissions from agriculture. Yet many of the abatement practices we have identified would have a net positive impact on farmers. They would allow much more sustainable agriculture in the long run; yields can be increased with reduced tillage and residue management; nutrient costs can be decreased with better nutrient application and reduced run-offs for cropland, rice and grassland; yields can be improved on degraded land by restoring them to their original state to reduce the risk of soil erosion; and the economics of cattle-raising can be improved with vaccines.

Agriculture is highly decentralized in most parts of the world and achieving the abatement potential requires a mix of government policies – appropriately enforced – and educational programs to change farming practices. Many experts argue that emissions abatement in agriculture is directly linked to the pace of economic development, making development policy particularly relevant given the high share of emissions in the developing world.

The complexity and the unpredictability of natural processes render measurement and monitoring of agricultural-emissions abatement extremely difficult. Furthermore, the fact that in most geographies farming often equates to living at the level of subsistence makes the assessment of pure climate-change issues insufficient. We note in particular:

- Agriculture, like the Forestry sector, faces several hurdles to effective abatement. These include "leakage" (e.g., organic soils restoration in one area leads to degradation of organic soils elsewhere); permanence (all carbon soil-enhancing measures such as reduced tillage face the risk of future disturbances releasing the carbon back to the atmosphere); additionality (proving that a project generates a reduction in emissions beyond that which would have occurred in its absence); and measurability/baselining (the complexity of measuring the impact, which can vary significantly from one region to the next);

104 The reason why the average cost of abatement rises to 2030 is that more expensive levers are implemented later in the period. For instance, we assume that livestock measures happen later on in the period as feed supplements are still in the development stage.

- Currently available measurement techniques generally fall short in assessing the interactions and interdependencies between the ecological, economic, and social impacts of agricultural-emissions abatement and the trade-offs in pursuing one measure at the expense of another;
- Many of the measurement techniques available today are not useful to farmers, being too time-consuming to implement in their day-to-day work and therefore making it difficult for them and their families to monitor progress on agricultural sustainability;
- Finally, many of the strategies relating to sustainable agriculture require 5–10 years of implementation (i.e., a full crop rotation) before they result in measurable evidence of payoff.

The challenge for successful GHG mitigation in the Agriculture sector will be to remove these barriers by implementing creative policies. Identifying policies that provide economic and social benefits as well as environmental sustainability will be critical for ensuring that effective GHG mitigation options are widely implemented in the future.

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# Appendix

## Appendix I – Contacts and acknowledgements

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| | |
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## Appendix II – Glossary

| | |
|---|---|
| **Abatement costs** | Additional costs (or net benefit) of replacing a technology in the reference/business-as-usual development by a low-carbon alternative. Measured as € per $tCO_2e$ abated emissions. Includes annualized CapEx repayments and Opex |
| **Abatement cost curve** | Compilation of abatement potentials and costs |
| **Abatement lever** | See “lever” |
| **Abatement potential** | Potential to reduce emissions of GHGs compared to the business-as-usual development by implementing an abatement lever. Measured in $tCO_2e$ per year. Only limited by technical constraints (e.g., maximum industry capacity build-up). Potential is incremental to business-as-usual |
| **Business-as-usual (BAU)** | Baseline emissions scenario to which abatement potential refers. Based primarily on external forecasts, e.g., IEA and EPA projections |
| **CapEx** | Incremental capital expenditure (investment) required for an abatement lever compared with business-as-usual |
| **CCS** | Carbon capture and storage – technologies for capturing and storing GHGs, mostly underground |
| **CDM (projects)** | Clean development mechanism – mechanism in the framework of the Kyoto Protocol that gives emitters of signatory states the option of investing in projects in developing countries under specified conditions and receiving $CO_2$ certificates for this |
| **CHP** | Combined heat and power (plant) |
| **CNG** | Compressed natural gas |
| **$CO_2$** | Carbon dioxide |
| **$CO_2e$** | Carbon dioxide equivalent is the unit for emissions that, for a given mixture and amount of greenhouse gas, represents the amount of $CO_2$ that would have the same global warming potential (GWP) when measured over a specified timescale (generally, 100 years) |
| **Decision maker** | The party that decides on making an investment, i.e., a company (e.g., as owner of an industrial facility) or an individual (e.g., as owner of a car or home) |
| **EAF** | Electric arc furnace – for steel production, in contrast to the integrated route of blast furnace and oxygen steel converter |

| | |
|---|---|
| **EU ETS** | Emissions Trading Scheme of the European Union |
| **€ or EUR** | Real 2005 Euro |
| **EV** | (Battery) Electric vehicle |
| **Frozen technology** | Increase in emissions due to growth in production considering the current (2005) technology level fixed over time, thus no decarbonization of current technologies or from new emerging technologies |
| **Greenhouse gas (GHG)** | Greenhouse gas in the context of the Kyoto Protocol, i.e., $CO_2$ (carbon dioxide), $CH_4$ (methane), $N_2O$ (nitrous oxide), HFC/PFC (hydrofluoro-carbons), and $SF_6$ (sulfur hexafluoride) |
| **Gt** | Gigatonne(s), i.e., one billion ($10^9$) metric tonnes |
| **GWP** | Global warming potential. An index, based upon radioactive properties of well-mixed greenhouse gases, measuring the radioactive forcing of a unit mass of a given well mixed greenhouse gas in today's atmosphere integrated over a chosen time horizon, relative to that of $CO_2$. The GWP represents the combined effect of the differing lenghts of time that these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time frame. |
| **HDV** | Heavy duty vehicle |
| **ICE** | Internal combustion engine |
| **IGCC** | Integrated gasification combined cycle – combined gas and steam turbine system with upstream coal gasification system |
| **kWh** | Kilowatt hour(s) |
| **(Abatement) lever** | Approach to reducing greenhouse gas emissions compared to the business-as-usual, e.g., use of more carbon-efficient processes or materials. Focus in this research has been on technical abatement levers, i.e., levers without a material impact on the lifestyle of consumers |
| **LDV** | Light duty vehicle |
| **MDV** | Medium duty vehicle |
| **Mt** | Megatonne(s), i.e., one million (1,000,000) metric tonnes |
| **MWh** | Megawatt hour(s), i.e., one million Watt hours |
| **OpEx** | Incremental operating cost required for the abatement lever compared to business-as-usual. Includes incremental operational and maintenance cost and incremental savings (e.g., from reduced energy consumption) |
| **PHEV** | Plug-in hybrid electric vehicle (see transport sector section for detailed definition) |

| | |
|---|---|
| **Sector** | Grouping of businesses or areas emitting GHGs, specifically:<br><br>***Power:*** Emissions from power and heat generation, including for local and district heating networks<br><br>***Industry:*** Direct emissions of all industrial branches with the exception of Power generation and the Transportation sectors. Indirect emissions are accounted for in the power sector<br><br>***Buildings:*** Direct emissions from private households and the tertiary sector (commercial, public buildings, buildings used in agriculture). Indirect emissions are accounted for in the power sector<br><br>***Transport:*** Emissions from road transport (passenger transportation, freight transportation), as well as sea and air transport<br><br>***Waste:*** Emissions from disposal and treatment of waste and sewage<br><br>***Forestry:*** Emissions from Land Use, Land Use Change and Forestry (LULUCF), mainly from deforestation, decay and peat<br><br>***Agriculture:*** Emissions from livestock farming and soil management |
| **t** | Metric tonne(s) |
| **TWh** | Terawatt-hour(s), i.e., one trillion ($10^{12}$) Wh |
| **$ or USD** | Real 2005 US Dollars |

## Appendix III – Methodology

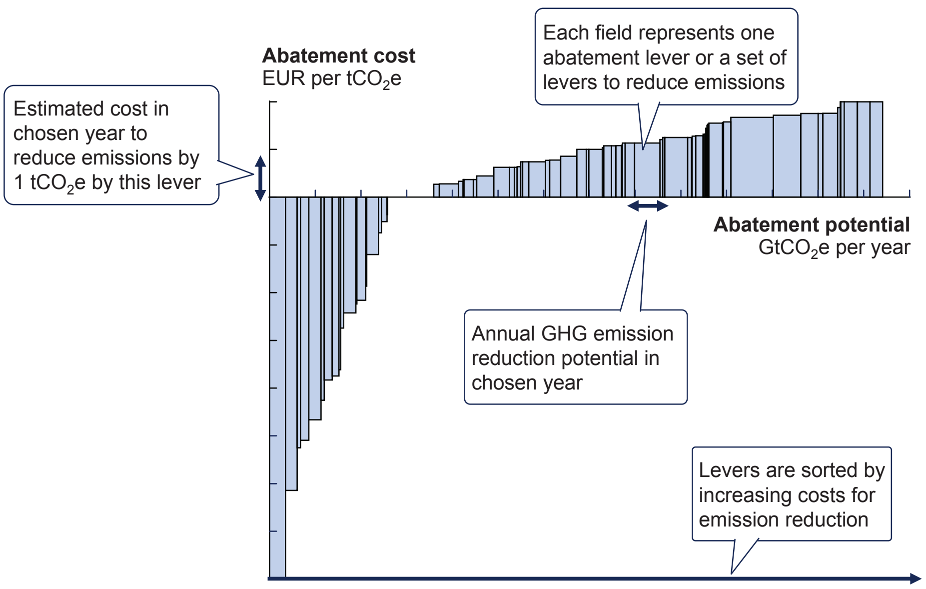
This section describes the methodological approach to the analysis of abatement (or mitigation) potentials, costs, and investments.

### Development of the Abatement Cost Curve

The combined axes of an abatement cost curve depict the available technical measures, their relative impact (emission volume reduction potential) and cost in a specific year (Exhibit A.III.1). Each bar is examined independently to quantify both dimensions.

**Exhibit A.III.1**

**Key cost curve dimensions**




Source: Global GHG Abatement Cost Curve v2.0

The basic logic of the cost curve is that it displays the abatement potential and corresponding cost for abatement "levers" relative to a business-as-usual (sometimes referred to as "reference case") scenario in a given year.

The width of each bar represents the economic *potential* (not a forecast) to reduce annual GHG emissions from that opportunity. The volume potential assumes concerted global action starting in 2010 to capture each opportunity. The potential reflects the total active installed capacity of that abatement lever in the year of the analysis, irrespective of when this capacity has been built.

The height of each bar represents the average cost of avoiding one metric tonne of $tCO_2e$ in the year of the analysis by each opportunity. The cost reflects the total active capacity of that opportunity, thus is a weighted average across sub-opportunities, regions, and years.

To ensure comparability across sectors and sources, all emissions and sinks have been measured in a common way, using $CO_2$ equivalents measured in metric tonnes ($tCO_2e$). The merit order of abatement levers is based on the lowest cost measures (in € per $tCO_2e$) as of 2030.

Viewed as a whole, the abatement cost curve illustrates the "supply" of abatement opportunities independently from a target (the possible "demand") for abatement. By definition, abatement potential is attributed to the sector in which the abatement lever is implemented. For example, if an abatement lever in a consuming sector (e.g., LEDs in buildings) reduces electricity consumption, the resulting emission reduction in the power sector is attributed to the consuming sector.

Therefore, the baseline for all consuming sectors includes indirect emissions from the power sector. The same relation as for electricity holds true for fossil fuel between the transport and petroleum and gas sectors. To avoid double counting of reductions, the production output in the producing sectors (power, petroleum and gas) is reduced accordingly before abatement measures in that sector are applied.

The uncertainty can be significant for both volume and cost estimates. There are two key sources of this uncertainty: what implementation is feasible to achieve in reality (highest in the Forestry and Agriculture sectors) and the cost development for key technologies.

## Calculating Abatement Potential

Abatement potential is defined as the volume difference between the emissions baseline and the emissions after the lever has been applied. The emissions baseline is calculated from several driver values, such as carbon intensity of a specific fossil fuel, production volume of a basic material or fuel consumption of a vehicle. Each abatement lever changes (usually reduces) specific driver values, for which the quantification is determined by literature and expert discussions. An illustrative example would be that fuel consumption can be reduced to 70% by passenger car improvements. This leads to an abatement potential of 30% of initial fuel combustion emissions.

Due to merit order logic of levers adhering to "lowest cost first" principle, the lever with the next higher cost is applied on a new baseline after reductions from all previous levers. Each abatement lever is assessed independently in each region.

## Calculating Abatement Costs

Abatement costs are defined as the incremental cost of a low-emission technology compared to the reference case, measured as € per $tCO_2e$ abated emissions. Abatement costs include annualized repayments for capital expenditure and operating expenditure. The cost does therefore represent the pure "project cost" to install and operate the low-emission technology. Capital availability is not considered a constraint.

Abatement costs are calculated according to the formula in Exhibit A.III.2. The full cost of a $CO_2e$ efficient alternative incorporates investment costs (calculated as annual repayment of a loan over the lifetime of the asset), operating costs (including personnel and materials costs), and possible cost savings generated by use of the alternative (especially energy savings). The full cost does not include transaction costs, communication/information costs, subsidies or explicit $CO_2$ costs, taxes, or the consequential impact on the economy (e.g., advantages from technology leadership).

**Exhibit A.III.2**

### Abatement cost formula

$$\text{Abatement cost} = \frac{[\text{Full cost of } CO_2e \text{ efficient alternative}] - [\text{Full cost of reference solution}]}{[CO_2e \text{ emissions from reference solution}] - [CO_2e \text{ emissions from alternative}]}$$

Operating expenditure is assessed as a real amount to be expensed in each year.

Capital expenditure is accounted for as annualized repayments. The repayment period is the functional life of the equipment. The interest rate used is the real long-term government bond rate of 4 percent, based on historical averages for long-term bond rates.

The cost curve takes a societal perspective instead of that of a specific decision-maker, illustrating cost requirements to the society. Given country differences in taxes, subsidies, interest rates and other cost components a global decision-maker perspective does not exist. This societal perspective enables the usage of the abatement cost curve as a fact base for global discussions about what levers exist to reduce GHG emissions, how to compare reduction opportunities and costs between countries and sectors, and how to discuss what incentives (e.g., subsidies, taxes, and $CO_2$ pricing) to put in place. For example, with this analysis, the question can be asked and answered, "If a government wanted to make different abatement measures happen, how much would different measures reduce emissions and what is the minimum cost (to achieve this emission reduction from a societal perspective)?"

All costs in the model are based on current cost and estimated projections. Estimates are based on best available projection methods, such as models (if available), expert views, and educated extrapolation. Given the long time horizon of approximately 25 years, a certain estimation error is inherent in the approach. Macroeconomic variables such as lifetime of assets, interest rates, oil prices, and exchange rates have the highest impact on results and error margins. Individual cost estimates per lever are of lower significance and will not substantially distort overall results for each lever.

Transaction costs – costs incurred in making an economic exchange above and beyond the technical project costs (e.g., education, policing, and enforcement costs) – are not included in the cost curve. Implementation cost for abatement levers are considered part of the transaction costs, involving such aspects as information campaigns and training programs.

Behavioral changes are also excluded from the cost curve, although they do present additional abatement potential. Behavioral changes are driven by various price and non-price factors, such as public education, awareness campaign, social trend, or policy changes. For this reason, behavioral shifts are analyzed separately from the primary cost curve as "further potential" with no abatement cost attached.

## Scope and parameters of the analysis

The analysis in this study covers all known anthropogenic GHG emissions globally.

The base year for the is 2005, with emissions and abatements projected for the years 2010, 2015, 2020, 2025 and 2030.

The cost curve model analyzes 10 sectors bottom-up in detail, 3 with top-down estimates and covers the entire world dividing it into 21 regions/countries. The bottom-up covered sectors are: power and heat, petroleum and gas, cement, iron and steel, chemicals, road transport, buildings, forestry, agriculture, and waste. The top-down assessed sectors are: other industry, sea transport, air transport. The breakdown for regions/countries is: Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Russia, South Africa, United Kingdom, United States, Middle East, Rest of Latin America, Rest of EU27, Rest of OECD Europe, Rest of Eastern Europe, Rest of Africa, Rest of developing Asia, Rest of OECD Pacific.

Following IPCC definitions, the abatement cost curve shows technical measures with economic potential under € 60 per $tCO_2e$.

Four criteria are applied to include a new technology in the cost curve:

- The technology is at least in the pilot stage.
- There is a widely shared point of view on the lever's technical and commercial viability in the medium term (starting by 2025 at the latest) and would therefore represent a significant contribution to reductions by 2030.
- Technological and economical challenges are well understood.
- There are compelling forces supporting the technology, such as policy or industry support, tangible benefits (e.g., energy security), or expected attractive economics.

Technologies excluded from the analysis include among others biodiesel from algae, biokerosene, CCS with Enhanced Gas Recovery, biomass gasification in power generation, wave and tidal power, and HCCI (Homogeneous Charge Compression Ignition) and camless valve actuation.

Key assumptions in this analysis include:

- Societal interest rate of 4 percent per annum
- Prices and costs are 2005 real values
- Oil price of $ 60 per barrel (IEA WEO 2007)
- Regional GDP and population compound growth rates shown in Exhibit A.III.3

These growth rates are the underlying drivers for the baseline from the IEA and are used to project GDP growth, which we then use as the basis for our financial comparisons. However, no demand elasticity has been modeled (e.g., GDP is not linked to changes in our assumptions on energy prices).

**Exhibit A.III.3**

## Macroeconomic data: regional real GDP and population growth rates

Annual growth rates, Percent

| | GDP development | | Population growth | |
|---|---|---|---|---|
| | 2005–15 | 2015–30 | 2005–15 | 2015–30 |
| North America | 2.6 | 2.2 | 1.0 | 0.7 |
| Western Europe | 2.3 | 1.8 | 0.1 | 0.0 |
| Eastern Europe* | 4.7 | 2.9 | -0.2 | -0.3 |
| OECD Pacific | 2.2 | 1.6 | 0.1 | -0.2 |
| Latin America | 3.8 | 2.8 | 1.2 | 0.9 |
| Rest of developing Asia** | 6.9 | 4.8 | 1.1 | 0.8 |
| Africa | 4.5 | 3.6 | 2.2 | 1.9 |
| China | 7.7 | 4.9 | 0.6 | 0.3 |
| India | 7.2 | 5.8 | 1.4 | 1.0 |
| Middle East | 4.9 | 3.4 | 2.0 | 1.5 |

* IEA nomenclature "Transition Economies"
** IEA nomenclature "Developing Asia"
Source: IEA WEO 2007

## Appendix IV – Comparison of results with IPCC AR4

### Power

| Power | **BAU baseline 2030** ($GtCO_2e$) | **Abatement potential 2030** ($GtCO_2e$) | **Explanation of key differences** |
|---|---|---|---|
| **IPCC AR4** | • 15.8<br>• Source: IEA WEO 2004 | • 2.4 / 3.6 / 4.7 (L/M/H) (Figure TS.27) | • Abatement from rooftop solar PV included in the Buildings sector in IPCC AR4, but in the Power sector in Global 2.0 (0.8 $GtCO_2e$ difference)<br>• Higher 2030 business as usual emissions in Global v2.0 than in IPCC AR4 (3 $GtCO_2e$ difference) – driven by an updated IEA projection – leads to higher abatement opportunities<br>• Global 2.0 includes early retirement of existing power plants as an implicit abatement lever (2 $GtCO_2e$ difference)<br>• Global 2.0 has higher growth expectations for selected technologies (0.5–1.0 $GtCO_2e$ difference).<br>• Total IPCC potential of 3.6 $GtCO_2e$ lower than sum of maximum potentials per technology (IPCC chapter 4, rationale: consolidation of all supply technologies and accounting for demand reduction effect). Comparison of maximum IPCC potential per technology with Global v2.0 gives an indication for overall difference:<br>– Similar maximum values expected for nuclear, geothermal, and hydro<br>– Global v2.0: substantially higher potential due to higher growth expectations for Solar CSP and Solar PV, Wind, and CCS<br>– IPCC: higher values for bioenergy and coal to gas shift. Lower values in Global v2.0 driven by the maximum renewable/nuclear growth scenario with cost based merit order logic, limiting potentials of coal to gas and bioenergy.<br>• Carbon intensity of power sector only differs by about 6% (IPCC: 500 $tCO_2e$/GWh, Global: 527 $tCO_2e$/GWh). This is therefore not the driver of substantial differences. |
| **Global v2.0** | • 18.7<br>• Source: IEA WEO 2007 | • 10.0 | |

## Industry

| Industry | BAU baseline 2030 ($GtCO_2e$) | Abatement potential 2030 ($GtCO_2e$) | Explanation of key differences |
|---|---|---|---|
| IPCC AR4 | • 22.3 (A1B) and 16.3 (B2), both incl. indirect emissions<br><br>• Petroleum and Gas: 1.4–2.9<br>• Cement: 3.8–6.4<br>• Iron and Steel: 1.8–4.2<br>• Chemicals (Ethylene and Ammonia): 0.6–1.0 | • 2.4 / 3.6 / 4.7 (L/M/H) (Figure TS.27) | • Relative mitigation potential of 25% very similar in both studies<br>• Smaller business as usual 2030 in IPCC AR4 report driven by lower production volume figures in some sectors (e.g. Iron and Steel) and exclusion of some electricity consuming sectors (e.g., fabrics, IT data centers). IPCC focuses in their "Other Industries" section on high GWP gas emitting industries<br>• Abatement potential from waste recycling allocated to each industry sector by the IPCC, whereas in Global v2.0 it is covered in the waste sector (0.9 $GtCO_2e$ in total)<br>• Subsector comparison:<br>– **Petroleum:** Lower potential in IPCC mainly driven by lower baseline, possibly only refining (downstream) included in IPCC. Global v2.0 includes downstream, midstream and upstream<br>– **Chemicals:** Lower potential in IPCC due to lower baseline, driven by scope definition differences (IPCC only ethylene and ammonia), and by production volume differences<br>– **Cement:** Slightly lower production forecast in Global v2.0 vs. IPCC AR4. Mitigation potential of Global v2.0 is at the lower range of the IPCC range, due to a) lower production forecast, b) lower relative abatement potential (Global 2.0 30%, IPCC AR4 40%)<br>– **Iron and steel:** Big differences in 2030 production volume forecasts (~2,500 Mt compared to ~1,100 Mt), leading to higher baseline and consequently higher abatement potential<br>– **Other industry:** Comparison not possible. In Global 2.0 this category includes light manufacturing, aluminum, pulp and paper. |
| Global v2.0 | • 29.1 (incl. indirect emissions)<br><br>• Petroleum and Gas: 3.9<br>• Cement: 3.9<br>• Iron and Steel: 5.5<br>• Chemicals: 5.3<br>• Other industry: 10.5 | • 7.3<br><br>• Petroleum and Gas: 1.1<br>• Cement: 1.0<br>• Iron and Steel: 1.5<br>• Chemicals: 2.0<br>• Other Industry: 1.7 | |

## Transport

| Road transport | BAU baseline 2030 ($GtCO_2e$) | Abatement potential 2030 ($GtCO_2e$) | Explanation of key differences |
|---|---|---|---|
| IPCC AR4 | • 6.6 (WBCSD) | • 0.7–0.8 for LDVs<br>• 0.6–1.5 for biofuels | • Commercial transport (MDVs/HDVs) not addressed by IPCC<br>• Global v2.0 baseline higher than IPCC/WBCSD as new research foresees higher LDV growth in the developing world.<br>• Higher LDV abatement potential in Global v2.0 due largely to the higher LDV growth expectation |
| Global v2.0 | • 8.1 (McKinsey) | • 2.4 (1.6 for LDVs, 0.3 for MDVs HDVs, 0.5 for biofuels) | |

| Sea transport | BAU baseline 2030 ($GtCO_2e$) | Abatement potential 2030 ($GtCO_2e$) | Explanation of key differences |
|---|---|---|---|
| IPCC AR4 | • 0.9 (WBCSD) | • n/a | • Different baseline sources<br>• Abatement potential in Sea transport not assessed by the IPCC |
| Global v2.0 | • 1.8 (IMO) | • 0.4 | |

| Air transport | BAU baseline 2030 ($GtCO_2e$) | Abatement potential 2030 ($GtCO_2e$) | Explanation of key differences |
|---|---|---|---|
| IPCC AR4 | • 1.4 (WBCSD) | • 0.3 | • No major differences |
| Global v2.0 | • 1.5 (ICAO) | • 0.4 | |

## Buildings – Residential and Commercial

| Buildings | BAU baseline 2030 ($GtCO_2e$) | Abatement potential 2030 ($GtCO_2e$) | Explanation of key differences |
|---|---|---|---|
| IPCC AR4 | • 14.3 (range 11.4 to 15.6) | • 5.4 / 6.0 / 6.7 (L/M/H) | • Reductions relative to business as usual are similar (IPCC 42%, Global v2.0 35%)<br>• Different sources for the business as usual emissions growth<br>• Abatement from rooftop solar PV included in the Buildings sector in IPCC AR4, but in the Power sector in Global 2.0 (0.8 $GtCO_2e$). If accounted for in Buildings, v2.0 indicates lower emissions after abatement than IPCC |
| Global v2.0 | • 12.6 | • 3.5 (4.3 if accounting for rooftop Solar PV in the buildings sector) | |

## Waste

| Waste | BAU baseline 2030 ($GtCO_2e$) | Abatement potential 2030 ($GtCO_2e$) | Explanation of key differences |
|---|---|---|---|
| IPCC AR4 | • 1.6 | • 0.4 / 0.7 / 1.0 (L/M/H) | • Abatement potential from waste recycling allocated to industry sector by the IPCC, whereas in Global v2.0 it is covered in the waste sector (0.9 $GtCO_2e$)<br>• Baseline and abatement potential very similar after taking this effect into account |
| Global v2.0 | • 1.7 | • 1.5 (0.6 without waste recycling) | |

## Forestry

| Buildings | **BAU baseline 2030** ($GtCO_2e$) | **Abatement potential 2030** ($GtCO_2e$) | **Explanation of key differences** |
|---|---|---|---|
| **IPCC AR4** | • n/a (but explained by IPCC authors) | • 1.3 / 2.8 / 4.2 (L/M/H bottom-up studies)<br>• 13.8 (top-down models) | • Global v2.0 abatement potential is in the middle of the range between IPCC AR4 estimates from global top-down models and from the collection regional models. In IPCC AR4 chapter 9 the bottom-up numbers were selected as more representative of the real situation, but it is admitted by IPCC authors that the numbers are probably lower than what the economic potential is, because implementation barriers are included. Compared to IPCC bottom-up models the Global v2.0 baseline is slightly lower.<br>• Global v2.0 substantially more conservative in afforestation, reforestation and forest management (2.8 vs. 9.8 $GtCO_2$) than IPCC AR4 top-down models, mostly due to conservative assumptions on land availability for afforestation activities<br>• Global v2.0 shows higher potential for avoided deforestation (5.0 vs 4.0 $GtCO_2$) than IPCC AR4 top-down models, in line with higher baseline assumptions on deforestation |
| **Global v2.0** | • 7.2 (5.2 deforestation (Houghton revised), 2 from peat (IPCC AR4) | • 7.8 | |

## Agriculture

| Waste | **BAU baseline 2030** ($GtCO_2e$) | **Abatement potential 2030** ($GtCO_2e$) | **Explanation of key differences** |
|---|---|---|---|
| **IPCC AR4** | • 8.0 to 8.4 | • 2.3 / 4.3 / 6.4 (L/M/H) | • No major differences |
| **Global v2.0** | • 7.9 | • 4.6 | |

## Appendix V – Summary result for 21 regions

The baseline emissions and the abatement potential for all 21 modeled regions are shown in Exhibit A.V.1. The reader should keep in mind that a key purpose of this global study is to achieve comparability across regions. Consequently, the same global sources for business-as-usual emissions were used for all regions and the same uniform methodology for structuring and quantifying abatement opportunities (however with regionally differing values). National abatement studies – such as the ones McKinsey has published for several of the world's largest economies – provide a much deeper view of the specifics of each respective country, and to a much larger extent rely on national baseline data and other national statistics. Also, in national studies additional levers are included, which are particularly relevant in that country. Consequently, baseline data and abatement potential can slightly differ between this global study and the national studies previously published by McKinsey.

**Exhibit A.V.1**

### Country/region split – BAU emissions and abatement potential

$GtCO_2e$ per year

| | | BAU Emissions | | | Abatement potential | |
|---|---|---|---|---|---|---|
| **Region Cluster** | **Country/region** | **2005** | **2020** | **2030** | **2020** | **2030** |
| North America | Canada | 0.6 | 0.8 | 0.9 | 0.2 | 0.4 |
| | United States* | 6.8 | 7.7 | 8.3 | 2.0 | 4.7 |
| Western Europe | France | 0.5 | 0.6 | 0.6 | 0.1 | 0.3 |
| | Germany | 1.0 | 1.1 | 1.1 | 0.2 | 0.4 |
| | Italy | 0.6 | 0.6 | 0.6 | 0.1 | 0.2 |
| | United Kingdom | 0.6 | 0.6 | 0.6 | 0.1 | 0.2 |
| | Rest of EU27 | 2.2 | 2.4 | 2.6 | 0.7 | 1.6 |
| | Rest of OECD Europe | 0.4 | 0.5 | 0.6 | 0.1 | 0.3 |
| Eastern Europe | Russia | 2.4 | 2.9 | 3.0 | 0.7 | 1.5 |
| | Rest of Eastern Europe | 0.7 | 0.9 | 0.9 | 0.2 | 0.5 |
| OECD Pacific | Japan | 1.3 | 1.5 | 1.4 | 0.3 | 0.6 |
| | Rest of OECD Pacific | 1.1 | 1.3 | 1.4 | 0.4 | 0.8 |
| Latin America | Brazil | 2.7 | 3.1 | 3.3 | 1.9 | 2.4 |
| | Mexico | 0.5 | 0.7 | 0.8 | 0.2 | 0.4 |
| | Rest of Latin America | 1.7 | 2.3 | 2.7 | 0.8 | 1.7 |
| Rest of developing Asia | Rest of developing Asia | 6.8 | 7.9 | 8.6 | 3.9 | 5.7 |
| Africa | South Africa | 0.4 | 0.6 | 0.7 | 0.2 | 0.5 |
| | Rest of Africa | 2.7 | 3.2 | 3.5 | 1.3 | 2.4 |
| China | China | 7.6 | 13.9 | 16.5 | 3.5 | 8.4 |
| India | India | 1.8 | 3.3 | 5.0 | 1.0 | 2.7 |
| Middle East | Middle East | 1.6 | 2.6 | 3.2 | 0.6 | 1.4 |
| Global Air & Sea Transport | Global Air & Sea Transport | 1.8 | 2.6 | 3.3 | 0.3 | 0.8 |
| | **Total** | **45.9** | **61.2** | **69.9** | **18.9** | **38.0** |

* Difference of 0.4 $GtCO_2e$ to 2005 baseline value of 7.2 $GtCO_2e$ reported in McKinsey's US cost curve report is due to accounting of air and sea transport emissions (accounted for at the global level in this report). Other differences impacting also 2020 and 2030 numbers are due to the fact that carbon sink effects in Forestry are not accounted for in the baseline in this report according to international policy principles. Also, the external baseline used for this report (IEA WEO 2007) has somewhat lower emission forecasts than the US report sources (EIA, DOE).

Source: Global GHG Abatement Cost Curve v2.0

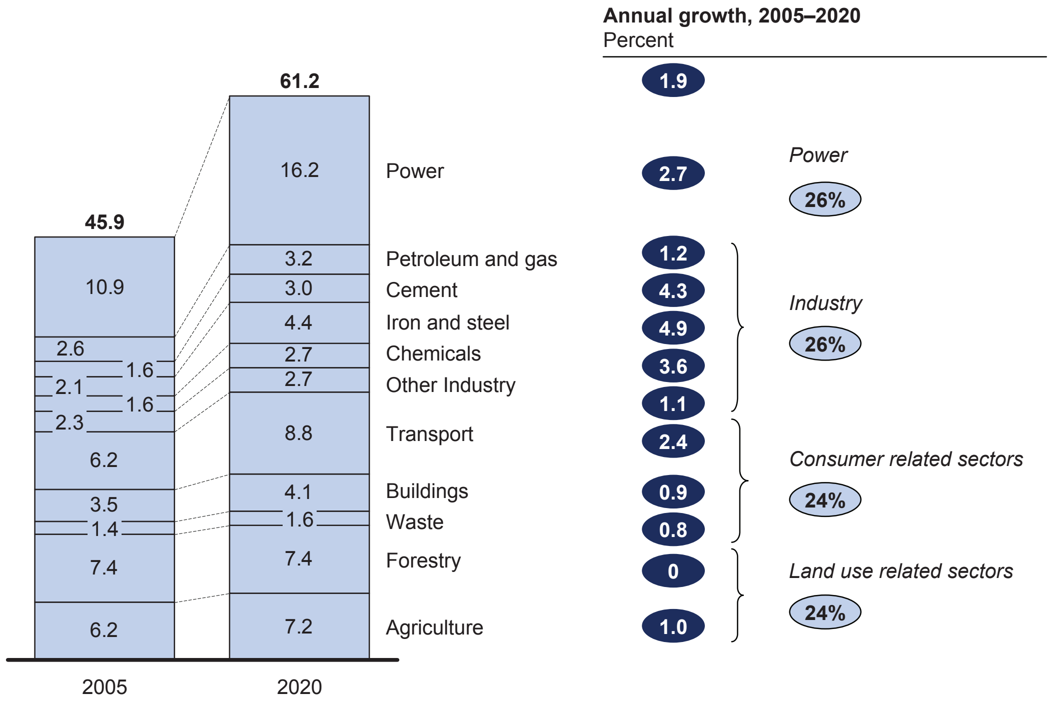
## Appendix VI – Abatement results for 2020

For comprehensiveness, we included below the key results of our analysis for 2020. The business-as-usual developments per sector and region can be found on Exhibit A.VI.1 and Exhibit A.VI.2, respectively. The cost curve is shown on Exhibit A.VI.3. Abatement potentials per sector and region and the emissions per capita development are depicted on Exhibit A.VI.4, Exhibit A.VI.5, and Exhibit A.VI.6. Investment requirements per sector (Exhibit A.VI.7) and per region (Exhibit A.VI.8) complete the 2020 perspective

**Exhibit A.VI.1**

**Business-as-usual emissions split by sector in 2005 and 2020**

$GtCO_2e$ per year

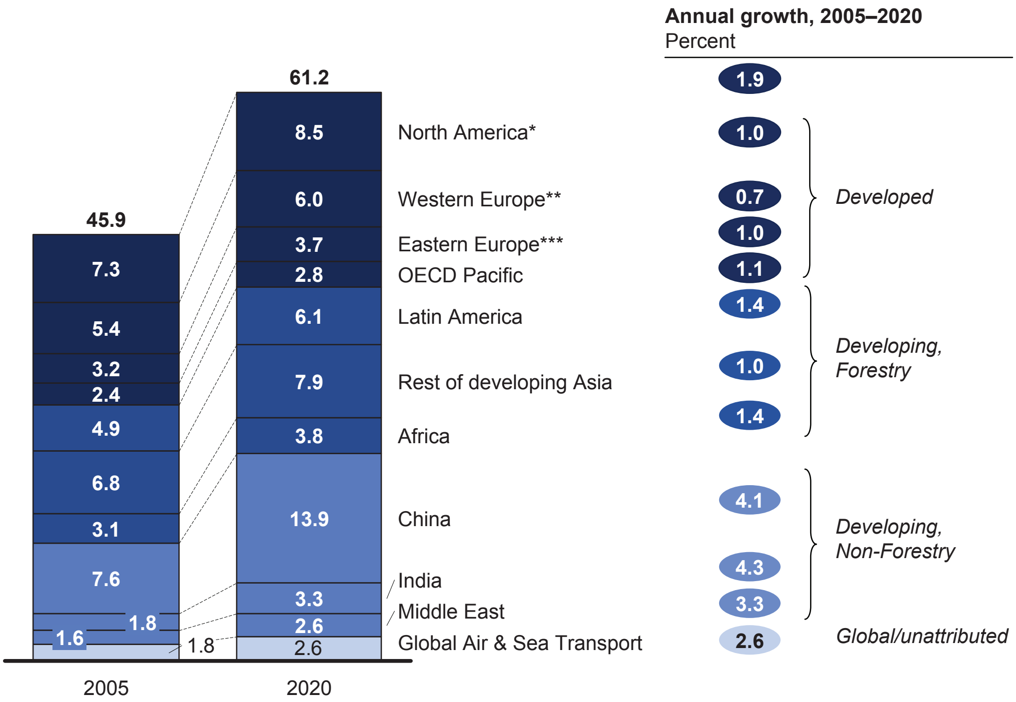



Source: Houghton; IEA; IPCC; UNFCCC; US EPA; Global GHG Abatement Cost Curve v2.0

Exhibit A.VI.2

## Business-as-usual emissions split by region in 2005 and 2020

$GtCO_2e$ per year

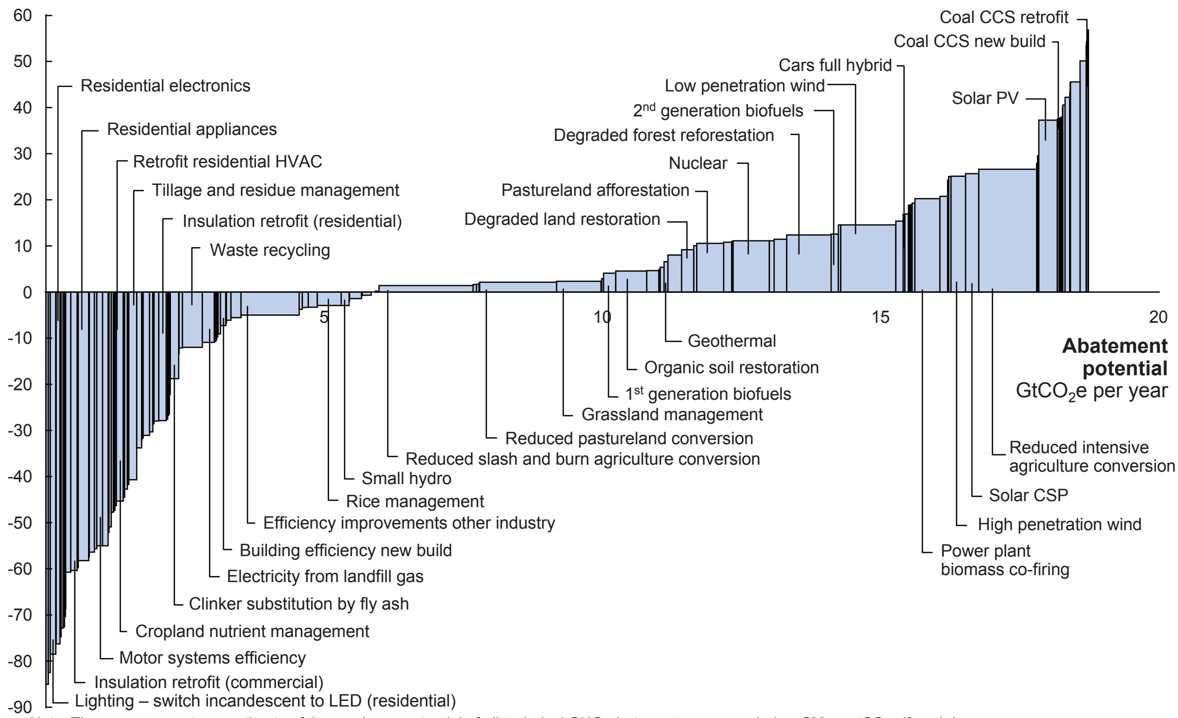



* US and Canada
** EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, and Switzerland
*** Non-OECD Eastern Europe and Russia.
Source: Houghton; IEA; IPCC; UNFCCC; US EPA; Global GHG Abatement Cost Curve v2.0

Exhibit A.VI.3

## Global GHG abatement cost curve beyond business-as-usual – 2020

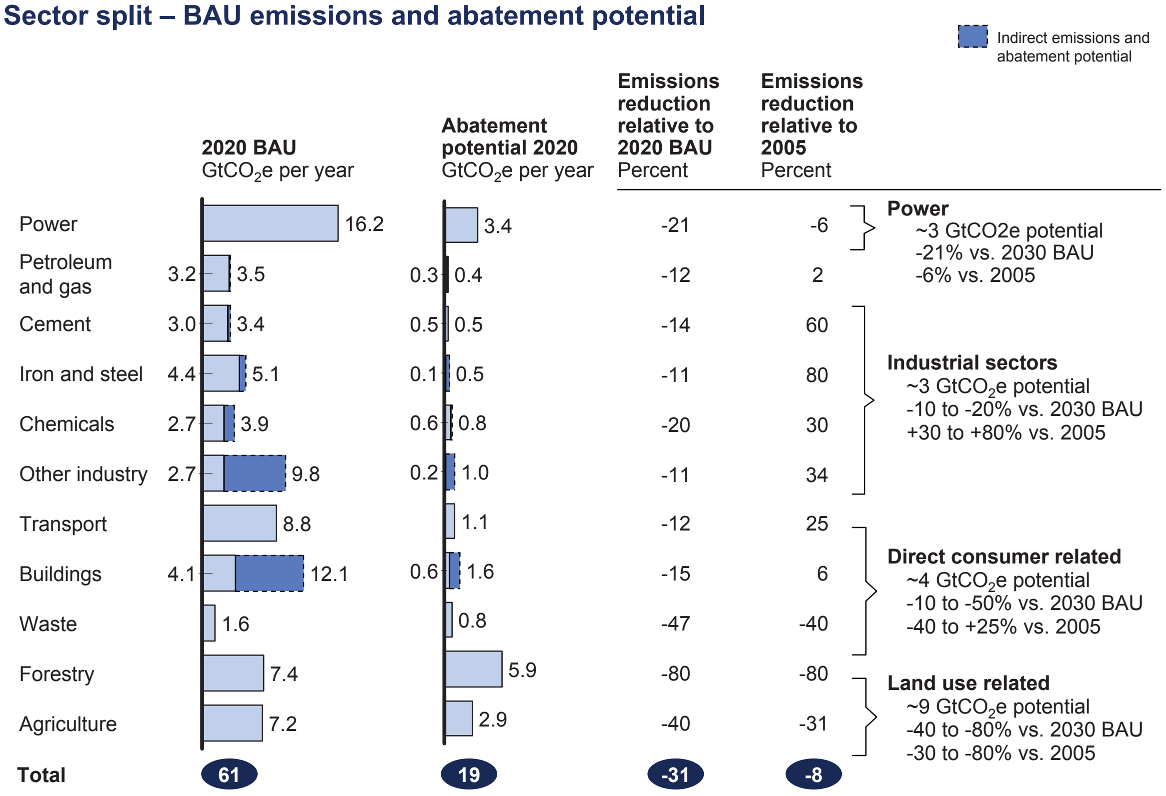
**Abatement cost**
€ per $tCO_2e$




Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per $tCO_2e$ if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

**Exhibit A.VI.4**

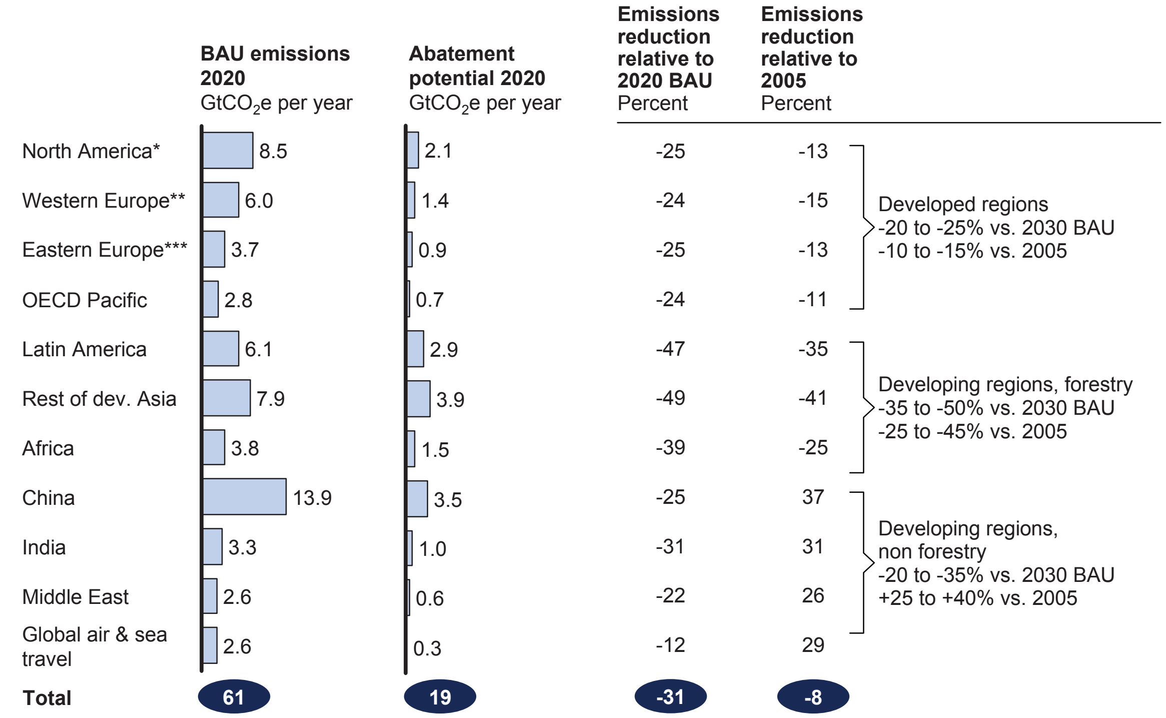
## Sector split – BAU emissions and abatement potential




Source: Global GHG Abatement Cost Curve v2.0

**Exhibit A.VI.5**

## Regional split – BAU emissions and abatement potential

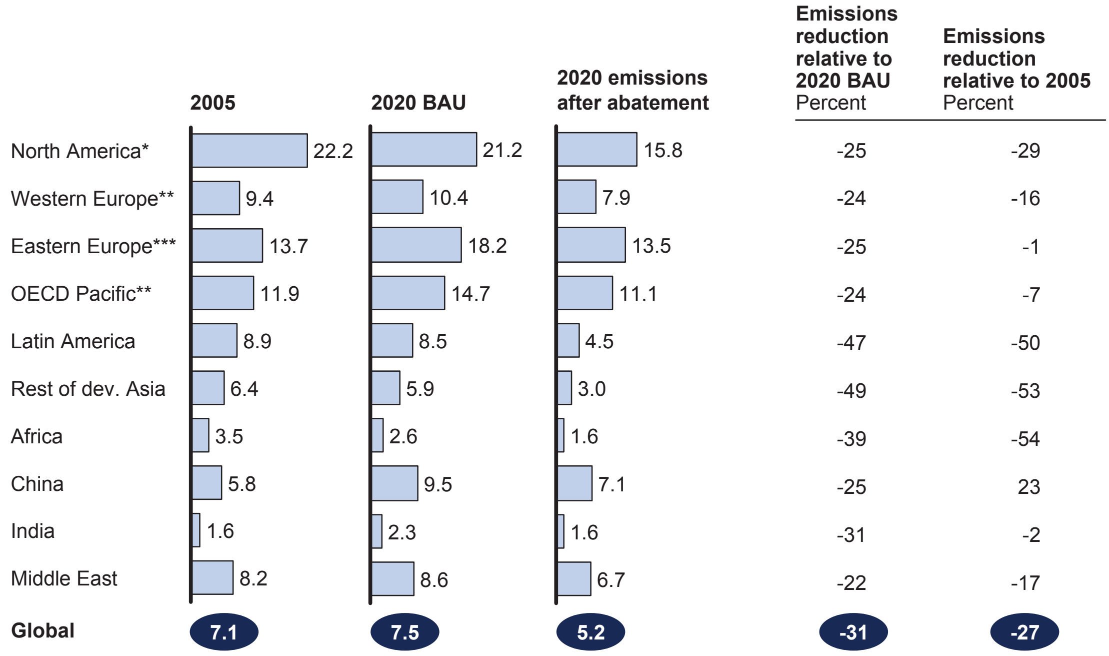



* United States and Canada
** Includes EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, Switzerland
*** Russia and non-OECD Eastern Europe
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; UNFCCC; US EPA

Exhibit A.VI.6

## Emissions per capita development

$tCO_2e$ per capita per year

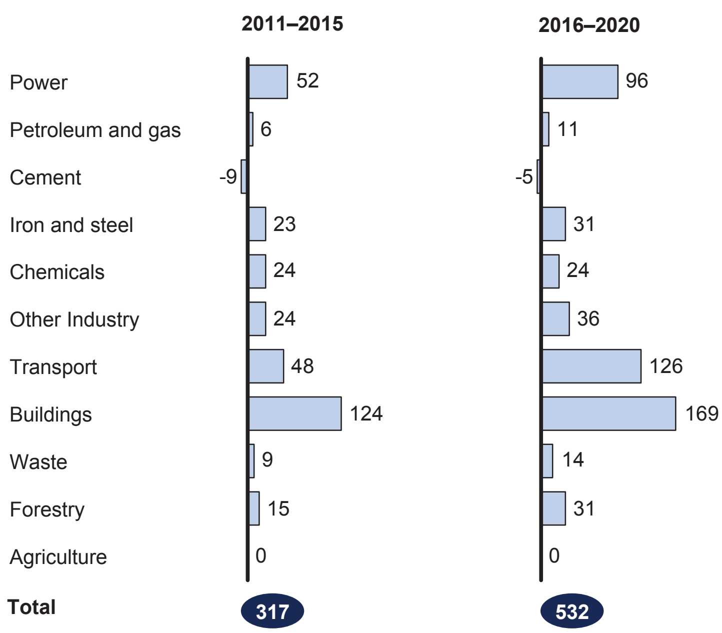



* United States and Canada
** Includes EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, Switzerland
*** Russia and non-OECD Eastern Europe
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; UNFCCC; US EPA

Exhibit A.VI.7

## Capital investment by sector incremental to business-as-usual for the abatement potential identified

€ billions per year; annual value in period

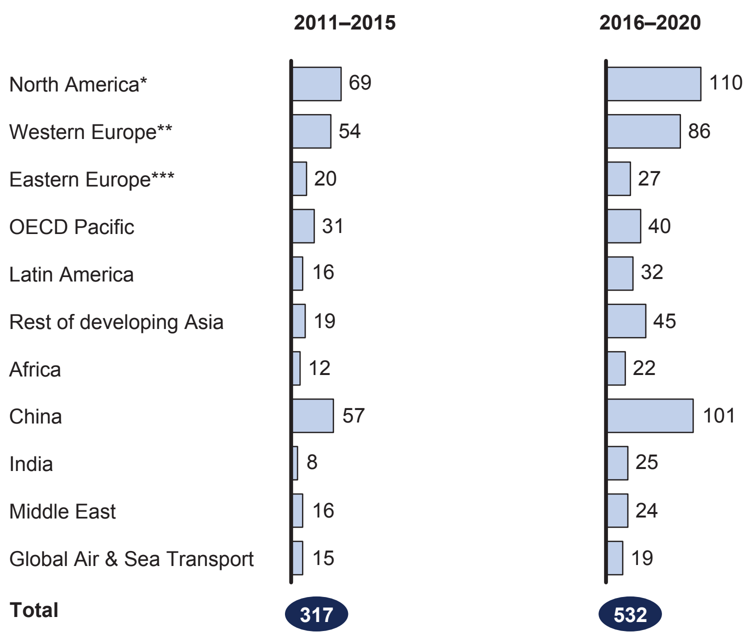



Source: Global GHG Abatement Cost Curve v2.0

**Exhibit A.VI.8**

## Capital investment by region incremental to business-as-usual for the abatement potential identified

€ billions per year; annual value in period




* United States and Canada
** Includes EU27, Andorra, Iceland, Lichtenstein, Monaco, Norway, San Marino, Switzerland
*** Russia and non-OECD Eastern Europe
Source: Global GHG Abatement Cost Curve v2.0

## Appendix VII – Assumptions by sector

For transparency, this appendix lists key assumptions for each abatement lever or group of abatement levers. For many assumptions, the uncertainty is considerable given the long time-lines involved, and the numbers quoted are the midpoint estimates used in our model.

### Power

| Lever | Key volume assumptions | Key cost and investment assumptions |
|---|---|---|
| **Wind** | • Volume growth constrained by two factors<br>– Maximum wind production growth rate capped at 20% per year in any given region (few markets have consistently grown faster over 25 years)<br>– Intermittent power sources (wind, solar PV) capped at 25% of production in any given region (wind 17–20%, solar 5–8%)<br>• Wind energy natural potential assumed to not be a constraining factor | • Average 2005 capex of € 1,300 per kW<br>• Overall cost per unit of electricity produced projected to decrease by ~5% with every doubling of cumulative installed capacity; these costs reductions reflect technology improvements but also decreasing resource quality with increasing penetration levels<br>• Integration costs for low penetration case (<10% wind penetration) between € 2–3 per MWh depending on geography and power mix in balancing area. Integration cost for high penetration case includes additional load following, regulation reserves and grid extensions costs, increasing to € 3 to 5 per MWh at 20% penetration (based on recent NREL report) |
| **Solar PV** | • Global panel supply industry: Annual production capacity assumed at 28 GW in 2012; thereafter annual growth rates capped at 20%<br>• Global production volume allocated to regions following radiation yield<br>• Growth of regional installation markets capped at 20% per year (few markets have consistently grown faster over 25 years)<br>• Intermittent power sources (wind, solar PV) capped at 25% of production in any given region (wind 17–20%, solar 5–8%) | • 2005 capex: € 3,500 per kW<br>• Capacity driven learning rate at 18% for every doubling of cumulative installed capacity (>20% historically)<br>• Capacity factor depending on region<br>• Integration costs modelled at similar levels as for wind (no/very limited empirical data available) |

| | | |
|---|---|---|
| **Solar Concen-trated (CSP)** | • Starting from very low installed base in 2005 to grow to a maximum potential 200 GW in 2030; industry growth 30% until 2015; 20% thereafter<br>• Significant storage capabilities assumed; increasing to 16 hours after 2020<br>• All assumptions from DLR report (see reference section) | • Total capex at € 4,500–6,000 per kW in base configuration, decreasing with a learning rate of 10%. High costs for storage compensated by increase in full load hours and thus power production<br>• Opex: decreasing from € 26.5 per MWh to € 14 per MWh in 2030<br>• Capacity factors depending on regional insolation and extent of storage facilities: 50—60% in 2020; increasing to 70–90% in 2030 with 16 hour storage (only deployed in regions with high insolation)<br>• All assumptions from DLR report (see reference section) |
| **Nuclear** | • Maximum global installed base 750 GW in 2030, based on estimates by WNA, IAEA and McKinsey; growth limited by engineering, construction and supply chain capacity constraints<br>• Regional split according to WNA assessment | • Due to limited experience with new construction and cost overruns in current projects, there is much uncertainty around capital costs for nuclear plants. Depending on the projects and the region, estimates range from € 1,500 to € 8,000 per kW. We assume a cost of € 3,000 per kW in 2005 in developed countries (€ 2,000 per kW is used for developing countries)<br>• OpEx is estimated conservatively at € 22/kWh, including fuel costs and waste disposal, maintenance costs, insurance, liabilities and decommissioning costs |
| **Geo-thermal** | • Very high theoretical potential for power generation; arguably 500 GW (USGS) in US alone<br>• US and developing Asia hold largest shares of current operating capacity, with about 30 percent each. Developing nations account for a large share of capacity planned or under construction<br>• Potential 2030 capacity estimated at 60–80 GW, corresponding to IGA estimate for global potential of conventional geothermal energy (corresponds to 50 percent of potential of Enhanced Geothermal Systems (EGS)) | • Capex: Average of € 3,000 per kW assumed (range from € 1,200 to 8,000 due to variations in local conditions) in 2005, with a capacity driven learning rate of 10%<br>• Opex: € 13 per MWh (range from 8 to 18 due to variations in local conditions)<br>• Capacity factor gradually increasing from 80% in 2005 to 90% in 2030 with technology improvements<br>• Large uncertainty around cost development |

| | | |
|---|---|---|
| **CCS** | • 50 plants assumed by 2020 (EU ambition of 12 plants extrapolated to global level)<br>• After 2020, assumption that CCS technology has been proven on a large scale and that it will "take off": CCS manufacturing industry is assumed to be able to grow by 30 percent through 2030, potentially supplying up to 4.5 $GtCO_2e$ of abatement globally in the most aggressive case. Based on the model dynamics and the availability of plants, CCS ends up using 3.3–4.1 Gt of that potential across all sectors by 2030 (Power sector Scenario A and Scenario B respectively)<br>• The Power sector shows the largest CCS potential (55 percent of the total) due to large point sources, availability of cheap fuel/electricity and suitable infrastructure | • High uncertainty on the cost side, as the technology has not yet been employed on such a large scale<br>• Costs are assumed to decrease with different development stages; in an early stage in 2015, we assume €60–70/tonne from a "cost to society" perspective (i.e., a 4 percent interest rate). From a business perspective (e.g., a 15 percent interest rate), the corresponding costs are €70–80/tonne. In 2030, the cost for CCS in the Power sector is forecast at €30–45/tonne. Base capex for new-build coal-fired power plants equipped with CCS is €2,700–3,200/kW (assuming a 40-year lifespan)<br>• Storage availability not assumed to be a significant bottleneck in the long term<br>• CCS-equipped plants that can sell the $CO_2$ for enhanced oil recovery (EOR) have an additional revenue stream, assumed at €20/tonne |
| **Biomass** | • 10% biomass co-firing is assumed on 50% of coal plants<br>• Volume of dedicated biomass plants in our model limited by total demand for new capacity in most geographic (as it is a higher cost option than many other low carbon technologies) | • Co-firing: biomass fuel cost and € 6 per kW in additional capex for minor modifications of fuel feed system<br>• Dedicated biomass plants are with our methodology (looking up to € 60 per tonne $CO_2e$) most attractive when large scale and equipped with CCS (as CCS costs less than € 60 per tonne $CO_2e$)<br>• Dedicated biomass capex: € 1,700 per kW (range from € 1,500 to 2,000 per kW) with learning rate of 5%; capacity factor is set to 80%, with a lifetime of 40 years |
| **Small hydro** | • Global 2030 potential of ~220 GW according to ESHA<br>• Potential in developed countries largely exploited but still considerable potential in developing Asia (40–50% of total capacity in Asia by 2030) | • Large variation in capex due to natural preconditions. Average of € 2,000 per kW developed countries; € 1,250 per kW developing countries (ESHA)<br>• Capacity factor is set to 35% |
| **Shift of coal new builds to gas** | • A share of the construction of new coal plants can be replaced by higher utilization of existing gas plants<br>• We assume an increase to 50 percent utilization possible, to leave ample room for gas plants to act as peak plants and back-up capacity for intermittent energy sources | • Avoided capex cost for coal new builds assumed as savings; higher opex determined by spark spread in given period |

## Petroleum and Gas – Upstream Production and Processing

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **Energy efficiency from improved behavior, maintenance and process control on retrofits** | • Energy conservation awareness programs<br>• Additional/improved maintenance that ensures equipment stays in optimal condition; i.e., monitoring and reduction of fouling (deposit build-up in the pipes)<br>• Improved process control that reduces suboptimal performance i.e., due to undesired pressure drops across gas turbine air filters, an undesired turbine washout frequency, suboptimal well and separator pressures | • Due to low priority historically given to efficiency in upstream, abatement potential assumed equal to max. abatement in downstream (levers 1 & 2 combined)<br>– EU: 9.0%<br>– US: 10.6%<br>– ROW: 9.4% | • Capex assumed equal to downstream in terms of cost per $tCO_2e$ abated (16 M€ per $MtCO_2e$)<br>• Savings based on (for all efficiency levers)<br>– Reduced fuel consumption (natural gas and fuel oil)<br>– Projected prices of fuels consumed |
| **Energy efficiency from improved maintenance and process control** | • Efficiency measures that involve replacement/ upgrades/additions that do not alter the process flow of an upstream production site<br>• More efficient pump impeller<br>• Replacement of boilers/ heaters/turbines/ motors | • Abatement potential assumed equal to minimum in downstream for lever 3 because of little opportunity for heat integration and more simple operations<br>– EU: 4.1%<br>– US: 6.5%<br>– ROW: 5.9% | • Capex assumed equal to downstream in terms of M€ per $MtCO_2e$ abated (€495 million per $MtCO_2e$)<br>• Opex estimated at 5% of total required Capex |
| **More energy efficient new builds** | • Program that ensures new built production sites use both process units with best-in-class energy efficiency as well as maintenance procedures and process controls that uphold the best-in-class energy efficiency | • Based on Energy Star Program and expert estimates, volume savings are estimated at<br>– EU: 13.1%<br>– US: 17.1%<br>– ROW: 15.3% | • Capex assumed equal to 80% of total costs for levers 1 & 2 as improvements can be implemented 'first time right' (€ ~409 million per $MtCO_2e$)<br>• Opex estimated at 5% of total required Capex |
| **Reduction of continuous, remote flaring** | • Measures to reduce continuous flaring by capturing the otherwise flared gas and bringing it to market, which will require<br>– Gas recovery and treating units for oil associated gasses<br>– Pipeline network to transport the gas | • Baseline flaring reduced by 72% between 2005–30<br>• Of remaining flares<br>– 90% assumed to be large enough for a gathering system<br>– 70% close enough for a transportation system<br>• 95% of flaring is from continuous flaring | • Capex<br>– € 320 million per BCM for the gathering system<br>– 50 km pipe per flare @ $ 0.5 million per km<br>• Average flare size of 2 mscf per day<br>• Opex estimated at 15% of total required Capex<br>• Savings result from reduced indirect electricity |

| | | | |
|---|---|---|---|
| **Carbon Capture and Storage (CCS)** | • Carbon capture and storage (CCS) is the sequestration of $CO_2$ from large emission point sources | • 80% of production sites assumed to be close enough to storage<br>• CCS technically feasible in 80% of sites<br>• 90% capture rate | • Capex € ~600 per $tCO_2e$ annual abatement capacity decreasing to ~200 in 2030<br>• Energy cost dependent on fuel mix and electricity prices<br>• Transport average 100 km @ 0.14 € per km decreasing to 0.10 in 2030<br>• € 11 per $tCO_2e$ storage cost increasing to 12 by 2030<br>• Overhead cost 15 € per $tCO_2e$, decreasing to 6 € per tonne in 2030 |

## Petroleum and Gas – Midstream Gas Transport and Storage

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **Replace compressor seals** | • Replacing traditional wet seals, which use high-pressure oil as a barrier against natural gas escaping from the compressor casing, with dry seals reduces methane leakage from compressors | • Based on Energy Star Program, Oil & Gas Journal and expert estimates, volume savings as percentage of total emissions are estimated at 82% of emissions from all dry seals which is<br>– ~7% of transmission leakage emissions or<br>– 2% of total emissions | • Capex<br>– € 160,000/ compressor for dry seals<br>– € 40,000/ compressor for wet seals<br>• Opex<br>– € 7,000/ compressor for dry seals<br>– € 49,000/ compressor for wet seals |
| **Improved maintenance on compressors** | • A directed inspection and maintenance (DI&M) program is a means to detect, measure, prioritize, and repair equipment leaks to reduce methane emissions from compressors, valves, etc.<br>– A DI&M program begins with a baseline survey to identify and quantify leaks. Repairs that are cost-effective to fix are then made to the leaking components<br>– Subsequent surveys are based on data from previous surveys, allowing operators to concentrate on the components that are most likely to leak and are profitable to repair | • Also based on Energy Star<br>– 15% leakage (not due to seals) worldwide is abated<br>– This represents 3% of total emissions | • No Capex<br>• Opex: € 133/ compressor |

| | | | |
|---|---|---|---|
| **DIM on distribution network** | • DIM program on the distribution network reduces leakage in a similar way as a DIM program on compressors but focuses on surface and metering stations | • Based on Energy Star Program and expert estimates<br>– 80% of the gap between current practice and technical best practice can be reduced<br>– Technical best practice is a 10% reduction of emissions in the region with current best practice<br>– This represents 5% of total emissions | • No Capex<br>• Opex: € 524,000/bcm (based on € 1,200 per kilometer of actively maintained pipe) |
| **Improved planning** | • Planning decreases emissions due to transmission combustion<br>– Planning reduces unnecessary (de-) pressurization by actively matching compression needs with natural gas demand<br>– In addition, emphasis is placed on running compressors at their most efficient point, called the working point | • Based on expert opinion<br>– Assume 7% reduction in fuel consumption<br>– This represents 2% of total emissions | • Capex: € 100,000/bcm<br>• Opex: 15% of Capex |

## Petroleum and Gas – Downstream Refining

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **Energy efficiency from behavioral changes** | • Energy conservation awareness programs including<br>– Energy and GHG awareness of personnel<br>– A review energy and GHG management system including monitoring KPIs vs. targets<br>– An energy management focus in all processes | • Based on Energy Star Program and expert estimates, abatement volume* is estimated at<br>– EU: 2.5–3.0%<br>– US: 2.9–3.5%<br>– ROW: 2.6–3.1% | • No Opex or Capex required<br>• Savings based on (for all efficiency levers)<br>– Reduced fuel consumption<br>– Projected prices of fuels consumed |
| **Energy efficiency from improved maintenance and process control** | • Additional/improved maintenance that ensures equipment stays in optimal condition; i.e., maintenance and monitoring of steam traps/steam distribution or monitoring and reduction of fouling (deposit build up in the pipes)<br>• Improved process control that reduces suboptimal performance i.e., due to undesired pressure drops across gas turbine air filters, an undesired turbine washout frequency, suboptimal well and separator pressures | • Different abatement volume estimates depending on whether refineries have implemented major energy efficiency programs<br>– EU: with 0.5–1.2%; without 2.5–6.0%<br>– US: with 0.6–1.4%; without 2.9–7.1%<br>– ROW: with 0.5–1.2%; without 2.6–6.2% | • Capex investment of USD 1 million required for a reference refinery (capacity of 180 MBBL/day) in a reference region (EU)<br>• Capex scaled by volume and regional factors<br>• Opex estimated at 15% of total required Capex |
| **Energy efficiency requiring Capex at process unit level** | • Efficiency measures that involve replacement/upgrades/additions that do not alter the process flow of a refinery<br>– Waste heat recovery via heat integration<br>– Replacement of boilers/heaters/turbines/motors | • Based on Energy Star Program and expert estimates, abatement volume* is estimated at<br>– EU: 4.1–4.3%<br>– US: 6.5–9.5%<br>– ROW: 5.9%-9.7% | • Capex investment of USD 50 million required for a reference refinery (capacity of 180 MBBL/day) in a reference region (EU)<br>• Capex scaled by volume and regional factors<br>• Opex delta estimated at 5% of total required Capex |

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| **Co-generation** | • Efficiency measure using Combined Heat and Power generation in which waste heat from power production is used in the refinery | • Co-generation capacity replaces 30% of thermal energy<br>• 60% of refineries technically capable of installing cogeneration<br>• Volume determined by the delta in carbon intensity between the of the power sector and co-generation | • Capex of 1 M€ per MW<br>• Opex estimated at 5% of total required Capex<br>• Co-generation assumed to run on natural gas<br>• Savings result from reduced indirect electricity and reduced fuel consumption of standard fuels (e.g., fuel oil) |
| **Carbon Capture and Storage (CCS)** | • Applying Carbon Capture and Storage to<br>– The exhaust emissions coming from direct energy use in the downstream refineries<br>– The emissions coming from the hydrogen generation unit | • Refineries processing >100 MBBL per day are large enough<br>• 80% of refineries assumed to be close enough to storage<br>• CCS technically feasible in 80% of refineries<br>• 90% capture rate | • Capex € ~600 per $tCO_2e$ annual abatement capacity decreasing to ~200 in 2030<br>• Energy cost dependent on fuel mix and electricity prices<br>• Transport average 100 km @ 0.14 € per km decreasing to 0.10 by 2030<br>• € 11 per t storage cost increasing to 12 by 2030<br>• Overhead cost € 15 per ton $CO_2$ abated, decreasing to € 6 per tonne in 2030 |

## Cement

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **Clinker replacement with fly ash** | • Reducing the clinker content in cement, by substituting clinker with slag, fly ash, and other mineral industrial components, reduces process and fuel combustion emissions as well as electric power from clinker production, which together accounts for over 90% of total emissions from the Cement industry | • Max share of clinker replacement with fly ash assumed 25%<br>• Used after all gypsum (5%) and available slag have been consumed | • Capex of 5 € per tonne for flyash handling capacity<br>• Material cost of 4 € per tonne & 13.5 € per tonne freight<br>• Minus avoided capex for clinker production capacity, electricity, fuel and clinker costs |
| **Clinker replacement with slag** | • As above | • Max share of clinker replacement with slag assumed 40%<br>• Preferred filler to start with (after 5% gypsum have been subtracted as general share) | • Capex 70 € per tonne for slag granulation capacity and 75 € per tonne for slag grinding capacity<br>• Material cost of 8 € per tonne and 13.5 € per tonne freight<br>• Minus avoided clinker opex and capex |
| **Clinker replacement with other MIC** | • As above | • Max share of clinker replacement with other MIC assumed 10%<br>• Unlimited availability assumed | • Capex of 60 € per tonne other MIC grinding capacity and 12 € per tonne handling capacity<br>• Material costs of 1.5 € per tonne<br>• Minus avoided clinker opex and capex |
| **Increased share of waste as kiln fuel** | • Burning alternative fuels, such as municipal or industrial fossil waste, or biomass instead of fossil fuels in the cement kiln to reduce average fuel combustion emissions of the clinker making process | • 2005 share set as RC, increased to 25% of energy required for clinker prod. 2030 globally<br>• Combustion reduces $CO_2e$ of alternative power use in incineration | • Capex of 200 € per tonne waste handling capacity<br>• Fuel costs of 5 € per tonne waste & 7 € per tonne OH<br>• Minus avoided costs for fossil fuels (differs by region based on fuel mix) |
| **Increased share of biomass as kiln fuel** | • Alternative fuels are assumed $CO_2e$ neutral, based on a life-cycle perspective for biomass and alternative usage considerations for waste fuels | • 2005 share assumed as reference scenario<br>• Increased to 8% of energy required for clinker production in 2030 globally | • Capex of 200 € per tonne waste handling capacity<br>• Fuel costs of 20 € per tonne biomass & 7 € per tonne OH<br>• Minus avoided costs for fossil fuels<br>• (differs by region based on fuel mix) |

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|---|---|---|---|
| **Carbon Capture and Storage – newbuilds** | • Carbon Capture and Storage (CCS) is the sequestration of $CO_2$ after it has been emitted due to fuel combustion and the clinker calcination process | • Implementation commencing in 2021<br>• Share of newbuild capacity 2021- 2025 assumed 13% and 2026–2030 assumed 37% on average per period | • Overhead cost € 15 per ton $CO_2$ abated, decreasing to € 6 per tonne in 2030<br>• Energy cost dependent on fuel mix and electricity prices<br>• $CO_2$ transport cost of 7 € per tonne $CO_2$ in 2030<br>• € 11 per tonne storage cost, increasing to € 12 per tonne in 2030<br>• Capex € ~600 per tonne new build $CO_2$ annual abatement capacity decreasing to € ~200 in 2030 |
| **Carbon Capture and Storage – retrofits** | | • Implementation commencing in 2026<br>• Share of retrofitted capacity assumed 4% for developing and 7% for developed countries on average between 2026–2030 | |
| **Waste heat recovery** | • Usage of excess heat from the clinker burning process for electricity generation using steam turbines driven by the flue gas exhaust stream | • 33% of clinker production capacity assumed to be equipped with waste heat recovery<br>• 15 KWh electricity generated per tonne clinker | • Capex of 12.9 € per tonne annual clinker capacity equipped<br>• Opex savings based on electricity cost |

Additionally, it is important to note that we assume the clinker share (clinker to cement ratio) in China to increase in the short term due to changes in product mix from 74% in 2005 to 78% in 2030 – this has significant effect on the short term as China produces 46% of cement globally in 2005. In the abatement case China will reach a level of 62% in clinker share in 2030.

## Iron and Steel

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **Co-generation** | • Blast Furnace/Basic Oxygen Furnace (BF/BOF) steel-manufacturing process generates gas as a by-product<br>• This gas can be recovered, cleaned and used for power generation<br>• Cogeneration can be integrated in the BF/BOF steel-manufacturing process to reduce the total energy demand | • All indirect energy in BF/BOF plants can be generated internally, allowing them to literally cut the power cord | • Capex of € ~70 per tonne steel production capacity<br>• 4 % interest rate (all levers)<br>• No opex cost delta<br>• Savings based on indirect energy prices (Power) |
| **Direct casting** | • Direct casting is a technique that integrates the casting and hot rolling of steel into one step, thereby reducing the need for reheat before rolling<br>• Near net-shape casting and strip casting are two newly developed direct casting techniques | • ~18% reduction in after treatment energy intensity<br>• Only applicable to new build | • Capex of € ~80 per tonne steel annual after treatment capacity, no opex cost delta<br>• Savings based on direct energy prices for fuel mix used in steel after treatment |
| **Smelt reduction** | • Smelt reduction is a technique that avoids the coking process by combining upstream hot metal production processes in one step<br>• The emission savings are achieved as less direct fuel is used when integrating preparation of coke with iron-ore reduction | • ~8% reduction of BF/BOF direct energy intensity | • Capex of € ~100 per tonne steel annual production capacity, no opex cost delta<br>• Savings based on direct energy cost for fuel mix used in direct BF/BOF plants |

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|---|---|---|---|
| **Energy efficiency** | • Annual improvement in direct energy efficiency above reference case, caused by a number of individual levers: Structural shift from BF/BOF to EAF production, better preventative maintenance, Improved process flow (management, logistics, IT-systems), motor systems, New efficient burners, Pumping systems, Capacity utilization management, Heat recovery, Sinter plant heat recovery, Coal moisture control, Pulverized coal injection | • 0.2–0.4% p.a. general energy efficiency increase above reference case (EE I), 0.2 % efficiency increase (EE II)<br>• Different improvement rates in EE I due to converging energy efficiencies globally | • Modeled as a net capex delta of € 25 or € 45 per tonne, respectively, abated $CO_2$e, no opex cost |
| **CCS** | • Carbon capture and storage (CCS) is the sequestration of $CO_2$ from large emission point sources<br>• Capture is modeled as post combustion, with chemical reactions "cleaning" the exhaust gases of $CO_2$ | • 90% capture rate, 90% of plants reaching enough scale<br>• 80% within reach of storage sites<br>• 0.24 MWh energy increase per tonne $CO_2$ separated in 2030<br>• 80% of old plants retrofittable due to technical constraints<br>• Implementation commencing in 2021 | • Overhead cost € 15 per tonne $CO_2$ abated, decreasing to € 6/tonne in 2030 (€ 19 and € 8 per tonne for retrofit)<br>• Transport average € 7 per tonne in 2030<br>• € 11 per tonne storage cost, increasing to € 12 per tonne 2030<br>• Capex € ~600 per tonne new build $CO_2$ annual abatement capacity decreasing to € ~200 in 2030 |
| **Coke substitution** | • Substituting coke used in BF/BOF furnaces with fuel based on biomass, with zero carbon intensity | • ~10% of coke possible to substitute<br>• ~100% carbon intensity decrease from carbon neutral biomass<br>• No substitution in reference case<br>• 100 % implementation by 2030 | • No capex required for fuel shift<br>• Savings based on indirect fuel price deltas for BF/BOF mills |
| **BF/BOF to EAF-DRI shift** | • Increased share of EAF-DRI relative BF/BOF in future steel making<br>• Direct Reduced Iron can be produced with natural gas as ore reducing agent. This DRI is used in EAF, replacing scrap. This replaces the reduction of iron ore with coke in BF/BOF process. | • Delta of BF/BOF and EAF-DRI carbon intensities driving abatement volume<br>• 10 % of BF/BOF steel production volume<br>• shifted by 2030<br>• No technology shift in reference case | • Capex difference of € ~200 per tonne steel annual production capacity<br>• No opex cost delta<br>• Opex savings or cost based on indirect energy prices |

## Chemicals

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **Motor systems** | • Introduction of energy saving measures in motor systems, such as adjustable speed drive, more energy efficient motors, and mechanical system optimization | • ~25% savings in indirect energy compared to standard systems<br>• 30 % implementation in RC, 100 % in AS by 2030 | • Capex of € ~50 per MWh installed base*<br>• No overhead cost delta<br>• Opex based on energy savings |
| **Adipic acid** | • Decomposition of the green house gas $N_2O$ (produced in the process of making adipic acid) into oxygen and nitrogen through the use of catalysts | • ~80–90% capture rate of $N_2O$ without lever (regional)<br>• 98 % capture with lever<br>• 10% in RC, 100% in AS by 2030 | • Capex of € ~10 per tonne acid (new build)<br>• Opex of € ~20 per tonne acid<br>• No significant energy delta |
| **Nitric acid** | • Applying filtering measures in order to decompose $N_2O$ from the tailgas of nitric acid production, where $N_2O$ is produced as a process emission | • ~7–9 tonne of $N_2O$ per Mtonne acid without lever (regional)<br>• ~1 ton of $N_2O$ per Mton acid with lever<br>• Not implemented in reference case, 100% in AS by 2030 | • Capex of € ~10 per ton acid<br>• Opex of € ~10 per ton acid<br>• No significant energy delta |
| **Fuel shift** | • Shifting direct energy use from coal powered systems to biomass powered systems, and oil powered systems to gas power, thereby lowering the carbon intensity per MWh energy produced given the lower carbon intensity of gas and biomass | • Biomass not part of RC, 80 % in AS new build, 50 % retrofit<br>• Gas not part of RC, 80 % in AS new build, 50% retrofit<br>• $CO_2e$ abatement based on combustion emissions by fuel | • Capex of € ~5 per MWh installed<br>• Opex based on difference of fuel prices<br>• No significant overhead costs assumed |
| **CCS Ammonia** | • Introduction of Carbon Capture and Storage to the $CO2_2$ emitted as a process emission from Ammonia production | • 90% capture rate, 90% of plants reaching enough scale<br>• 80% within reach of storage sites<br>• 0.24 MWh energy increase per ton $CO_2$ separated in 2030 (0.15 for ammonia separation)<br>• 80% of old plants retrofittable<br>• Implementation commencing in 2021 | • Overhead cost € 15 per ton $CO_2$ abated, decreasing to € 6 per tonne in 2030 (€ 19 and € 8 per tonne for retrofit)<br>• Transport average € 7 per tonne in 2030<br>• € 11 per tonne storage cost, increasing to € 12 per tonne in 2030<br>• Capex € ~600 per tonne new build $CO_2$ annual abatement capacity decreasing to € ~200 in 2030 |
| **CCS Direct** | • Applying Carbon Capture and Storage to the exhaust emissions coming from direct energy use in the chemical plants | | |

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|---|---|---|---|
| **Process intensification** | • Process intensification in chemical processes, leading to an annual emission decrease. The improvements are caused by a number of individual levers, including continuous processes, improved process control, preventative maintenance, more efficient burners and heaters and logistical improvements | • 0.1–0.25% p.a. process intensification and catalyst optimization above RC<br>• Different improvement rates regionally due to converging energy efficiencies globally<br>• Modeled in three steps, with increasing costs<br>• Both levers split in two buckets: “process “and “energy”, affecting the corresponding emission type in baseline | • Capex modeled as the net delta per $tCO_2e$ annual abatement potential in three steps, € 0, ~200, and ~400 per tonne<br>• Opex modeled as net opex delta per abated $tCO_2e$ in similar steps @ € 0, 10, and 20 per $tCO_2e$ |
| **Catalyst optimization** | • Catalyst optimization in chemical processes, leading to an annual process and direct energy emissions decrease above the reference case. The improvements are caused by a number of individual levers, including improved chemical structure of catalysts, design to lower reaction temperatures, and chain reaction improvements | | |
| **CHP** | • CHP, combined heat and power, is a technique to involve the energy losses in power production to generate heat for processes, in order to increase system efficiency and decrease the amount of fuel needed for power generation | • 15% savings in direct power (regional) compared to heating systems without CHP<br>• 0% implementation in RC, 100 % in abatement case by 2030 | • Capex of € ~55 per MWh existing direct power in a given plant<br>• Opex based on fuel savings |
| **Ethylene cracking** | • Ethylene Cracking improvement includes furnace upgrades, better cracking tube materials and improved separation and compression techniques that lowers the direct energy used in the cracking process | • ~1.1 MWh savings per ton Ethylene compared to standard cracking processes<br>• 0% implementation in RC, 100 % in abatement case by 2030 | • Capex of € ~50 per tonne Ethylene production<br>• Overhead cost of € ~25 per tonne Ethylene<br>• Opex largely driven by energy savings (1.1 MWh per tonne) |

## Transport/LDVs: gasoline, diesel

| Lever | | Description | Key volume assumptions | Key cost assumptions Initial cost | Reduced cost 2030 |
|---|---|---|---|---|---|
| ICE fuel efficiency improvments – gasonline | **Bundle G1** | • Variable valve control<br>• Engine friction reduction (mild)<br>• Low rolling resistance tires<br>• Tire pressure monitoring system<br>• Mild weight reduction | • ICE World scenario: 21% in 2011–2015, 21% in 2016–2020, 2% in 2021–2025<br>• Mixed Tech scenario: 20% in 2011–2015, 20% in 2016–2020, 1% in 2021–2025<br>• Hybrid/Electric World scenario: 20% in 2011–2015, 20% in 2016–2020, 1% in 2021–2025 | € 307 (2010) | € 185 |
| ICE fuel efficiency improvments – gasonline | **Bundle G2** | • Bundle G1+<br>• Medium displacement reduction (“downsizing”)<br>• Medium weight reduction<br>• Electrification (steering, pumps)<br>• Optimized gearbox ratio<br>• Improved aerodynamic efficiency<br>• Start-stop | • ICE World scenario: 18% in 2011–2015, 24% in 2016–2020, 9% 2021–2025, 3% 2026–2030<br>• Mixed Tech scenario: 17% in 2011–2015, 22% in 2016–2020, 7% 2021–2025, 2% 2026–2030<br>• Hybrid/Electric World scenario: 17% in 2011–2015, 21% in 2016–2020, 6% 2021–2025, 1% 2026–2030 | € 1,116 (2010) | € 673 |
| ICE fuel efficiency improvments – gasonline | **Bundle G3** | • Bundle G2+<br>• Strong displacement reduction (“downsizing”)<br>• Air conditioning modification<br>• Improved aerodynamic efficiency<br>• Start-stop system with regenerative braking | • ICE World scenario: 8% in 2011–2015, 35% in 2016–2020, 35% 2021–2025, 6% 2026–2030<br>• Mixed Tech scenario: 7% in 2011–2015, 30% in 2016–2020,27% 2021–2025, 4% 2026–2030<br>• Hybrid/Electric scenario: 7% in 2011–2015, 22% in 2016–2020, 24% 2021–2025, 3% 2026–2030 | € 1,794 (2010) | € 1,081 |
| ICE fuel efficiency improvments – gasonline | **Bundle G4** | • Bundle G3+<br>• Direct injection (homogeneous)<br>• Strong weight reduction (9%)<br>• Optimized transmission (including dual clutch, piloted gearbox) | • ICE World scenario: 0% in 2011–2015, 14% in 2016–2020, 54% 2021–2025, 90% 2026–2030<br>• Mixed Tech scenario: 0% in 2011–2015, 12% in 2016–2020, 37% 2021–2025, 54% 2026–2030<br>• Hybrid/Electric scenario: 0% in 2011–2015, 10% in 2016–2020, 29% 2021–2025, 38% 2026–2030 | € 2,593 (2010) | € 1,563 |
| **Gasoline – Full hybrid** | | • Bundle G4 + Full hybrid | • ICE World scenario: 1% in 2011–2030<br>• Mixed Tech scenario: 3% in 2011–2015, 8% in 2016–2020, 16% 2021–2025, 22% 2026–2030<br>• Hybrid/Electric scenario: 1% in 2011–2015, 11% in 2016–2020, 21% 2021–2025, 25% 2026–2030 | € 3,498 (2010) | € 1,848 |

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| **Gasoline – Plug-in hybrid** | | • 60 km range – 66% electric share;<br>• Energy demand electric drive 250 Wh per km | • ICE World scenario: 0% in 2011–2030<br>• Mixed Tech scenario: 0% in 2011–2015, 3% in 2016–2020, 11% 2021–2025, 17% 2026–2030<br>• Hybrid/Electric scenario: 1% in 2011–2015, 4% in 2016–2020, 15% 2021–2025, 24% 2026- | € 12,217 (2010) | € 3,530 |
| **Electric vehicle** | | • 200 km range<br>• Energy demand 250 Wh/km | • ICE World scenario: 0% in 2011–2030<br>• Mixed Tech scenario: 0% in 2011–2015, 1% in 2016–2020, 1% 2021–2025, 2% 2026–2030<br>• Hybrid/Electric scenario: 1% in 2011–2015, 2% in 2016–2020, 5% 2021–2025, 9% 2026- | € 26,336 (2010) | € 5,764 |
| **ICE fuel efficiency improvement – Diesel** | **Bundle D1** | • Medium downsizing<br>• Engine friction reduction<br>• Low rolling resistance tires<br>• Tire pressure monitoring system<br>• Mild weight reduction (1.0%) | • ICE World scenario: 21% in 2011–2015, 20% in 2016–2020, 3% 2021–2025<br>• Mixed Tech scenario: 20% in 2011–2015, 19% in 2016–2020, 3% 2021–2025<br>• Hybrid/Electric World scenario: 23% in 2011–2015, 19% in 2016–2020, 3% 2021–2025 | € 1,084 (2006) | € 899 |
| | **Bundle D2** | • Bundle D1 +<br>• Piezo injectors<br>• Medium downsizing<br>• Medium weight reduction<br>• Electrification (steering, pumps)<br>• Optimized gearbox ratio<br>• Improved aerodynamic efficiency | • ICE World scenario: 21% in 2011–2015, 29% in 2016-2020, 14% in 2021–2025, 5% in 2026–2030<br>• Mixed Tech scenario: 20% in 2011–2015, 27% in 2016–2020, 11% 2021–2025, 4% 2025–2030<br>• Hybrid/Electric World scenario: 22% in 2011–2015, 27% in 2016–2020, 10% 2021-2025, 4% 2025–2030 | € 1,396 (2006) | € 1,087 |
| | **Bundle D3** | • Bundle D2 +<br>• Torque oriented boost<br>• Air conditioning modification<br>• Improved aerodynamic efficiency<br>• Start-stop system with regenerative braking | • ICE World scenario: 8% in 2011–2015, 29% in 2016–2020, 34% in 2021–2025, 13% in 2026–2030<br>• Mixed Tech scenario: 7% in 2011–2015, 25% in 2016–2020, 27% in 2021–2025, 9% in 2026–2030<br>• Hybrid/Electric scenario: 7% in 2011–2015, 23% in 2016–2020, 24% 2021–2025, 9% in 2026- | € 1,984 (2006) | € 1,441 |
| | **Bundle D4** | • Bundle D3 +<br>• Increase injection pressure<br>• Strong downsizing (instead of medium downsizing)<br>• Strong weight reduction | • ICE World scenario: 0% in 2011–2015, 16% in 2016–2020, 46% 2021–2025, 80% in 2026–2030<br>• Mixed Tech scenario: 0% in 2011–2015, 13% in 2016–2020, 34% in 2021–2025, 56% in 2026–2030<br>• Hybrid/Electric scenario: 0% in 2011–2015, 11% 2016–2020, 31% 2021–2025, 46% in 2026–2030 | € 2,349 (2006) | € 1,661 |

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| **Diesel – Full hybrid** | • Bundle D4 + Full hybrid | • ICE World scenario: 0% in 2011–2030<br>• Mixed Tech scenario: 3% in 2011–2015, 8% in 2016–2020, 15% in 2021–2025, 20% in 2025–2030<br>• Hybrid/Electric scenario: 0% in 2011–2015, 8% 2016–2020, 18% in 2021–2025, 23% 2026- | € 4,962 (2010) | € 2,512 |
| **Diesel – Plug-in hybrid** | • 60 km range – 66% electric share<br>• Energy demand electric drive 250 Wh per km | • ICE World scenario: 0% in 2011–2030<br>• Mixed Tech scenario: 0% in 2011–2015, 3% in 2016–2020, 8% 2021–2025, 10% 2025–2030<br>• Hybrid/Electric scenario: 0% in 2011–2015, 5% in 2016–2020, 13% 2021–2025, 18% 2026–2030 | € 12,217 (2010) | € 3,530 |
| **CNG vehicle** | • Fuel economy 2.92–4.43 litres natural gas per 100 km<br>• Combustion emissions 1,740 g $CO_2e$ per l natural gas<br>• Energy content 31.6 MJ per l natural gas | • ICE World scenario: 0% in 2011–2030<br>• Mixed Tech scenario: 0% in 2011–2030<br>• Hybrid/Electric scenario: 0% in 2011–2015, 0% 2016–2020, 1% in 2021–2025, 1% 2026–2030 | € 4,274 (2010) | € 2,576 |

## Transport/MDVs

| Lever | | Description | Key volume assumptions | Key cost assump-tions Initial cost | Reduced cost 2030 |
|---|---|---|---|---|---|
| MDV ICE fuel efficiency improvements | **Bundle 1** | • Rolling resistance reduction | • 30% in 2011–2015<br>• 10% in 2016–2020<br>• 0% in 2030- | € 637 (2008) | € 637 |
| | **Bundle 2** | • Rolling resistance reduction<br>• Aerodynamics improvement | • 30% in 2011–2015<br>• 10% in 2016–2020<br>• 0% in 2021–2030 | € 637 (2008) | € 1,273 |
| | **Bundle 3** | • Rolling resistance reduction<br>• Conventional ICE improvement incl. mild hybrid | • 20% in 2011–2015<br>• 40% in 2016–2020<br>• 50% in 2021–2030 | € 5,943 (2008) | € 2,759 |
| | **Bundle 4** | • Rolling resistance reduction<br>• Aerodynamics improvement<br>• Conventional ICE improvement incl. mild hybrid | • 20% in 2011–2015<br>• 40% in 2016–2020<br>• 50% in 2021–2030 | € 5,943 (2008) | € 3,396 |
| **Full hybrid** (not in cost curve) | | • Rolling resistance reduction<br>• Aerodynamics improvement<br>• Conventional ICE improvement incl. mild hybrid<br>• Full hybrid technology | • Not in cost curve | € 48,391 (2008) | € 24,620 |
| **Plug-in hybrid** (not in cost curve) | | • Rolling resistance reduction<br>• Aerodynamics improvement<br>• Conventional ICE improvement incl. mild hybrid<br>• Full hybrid technology<br>• Plug-in hybrid technology | • Not in cost curve | € 68,281 (2008) | € 44,510 |

## Transport/HDVs

| Lever | | Description | Key volume assumptions | Key cost assumptions Initial cost | Reduced cost 2030 |
|---|---|---|---|---|---|
| HDV ICE fuel efficiency improvements | **Bundle 1** | • Rolling resistance reduction | • 30% in 2011–2015<br>• 6% in 2016–2020<br>• 0% in 2021–2030 | € 2,122 (2010) | € 2,122 |
| | **Bundle 2** | • Rolling resistance reduction<br>• Aerodynamics improvement | • 30% in 2011–2015<br>• 14% in 2016–2020<br>• 0% in 2021–2030 | € 2,441 (2010) | € 3,714 |
| | **Bundle 3** | • Rolling resistance reduction<br>• Conventional ICE improvement incl. mild hybrid | • 20% in 2011–2015<br>• 24% in 2016–2020<br>• 25% in 2021–2025<br>• 20% in 2026–2030 | € 12,734 (2010) | € 7,428 |
| | **Bundle 4** | • Rolling resistance reduction<br>• Aerodynamics improvement<br>• Conventional ICE improvement incl. mild hybrid | • 20% in 2011–2015<br>• 56% in 2016–2020<br>• 75% in 2021–2025<br>• 80% in 2026–2030 | € 13,053 (2010) | € 9,020 |
| **Full hybrid** (not in cost curve) | | • Rolling resistance reduction<br>• Aerodynamics improvement<br>• Conventional ICE improvement incl. .mild hybrid<br>• Full hybrid technology | • Not in cost curve | € 55,501 (2010) | € 40,856 |

## Transport Biofuels

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|---|---|---|---|---|
| **1st Gen. Biofuels** | • Modeled as sugarcane ethanol (26 g$CO_2$e per MJ) | • Gasoline biofuel volume: 5.75% in BAU, 25% in abatement case (14.5% 1st generation biofuels (4% corn/maize, 10.5% sugarcane), 10.5% 2nd generation biofuels (lignocellulosic))<br>• Diesel: 3.3% in BAU, 3.3% in abatement case | $ 1.30 per gallon | $ 1.30 per gallon |
| **2nd Gen. Biofuels** | • Modeled as ligno-cellulosic ethanol (25 g$CO_2$e per MJ) | | – | $ 1.38 per gallon |

## Buildings – Residential

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **New build efficiency package (incl. insulation)** | • Achieve energy consumption levels comparable to passive housing<br>– Reduce demand for energy consumption through improved building design and orientation<br>– Improve building insulation and airtightness; improve materials and construction of walls, roof, floor, and windows<br>– Ensure usage of high efficiency HVAC and water heating systems | • Assume that maximum site energy consumption for HVAC and water heating in new builds is 132 kWh per $m^2$<br>• New technology results in 20 kWh per $m^2$ in developing warm countries, 30 kWh per $m^2$ in developing cold countries, and 35 kWh per $m^2$ in developed countries (SITE energy) | • In 2005, 6-7% cost premium on new builds<br>• By 2020:<br>– Developing regions 5% cost premium on new builds with "high efficiency package."<br>– 4% premium in developed regions<br>• US initial construction costs validated with experts, and scaled to global regions |
| **Insulation retrofit building package, level 1 and level 2** | • Level 1 retrofit - "basic retrofit" package<br>– Improve building airtightness by sealing baseboards and other areas of air leakage<br>– Weather strip doors and windows<br>– Insulate attic and wall cavities<br>– Add basic mechanical ventilation system to ensure air quality<br>• Level 2 retrofit<br>– Retrofit to "passive" standard, in conjunction with regular building renovations<br>– Install high efficiency windows and doors; increase outer wall, roof, and basement ceiling insulation; mechanical ventilation with heat recovery, basic passive solar principles | • Level 1 retrofit based on 15-25% heating savings potential and up to 10% cooling savings potential, adjusted by income and climate<br><br>• Level 2 retrofit can reach heating/cooling consumption of 20-35 kWh per $m^2$ (SITE energy) | • Level 1 retrofit based on 6.26 € per $m^2$ in W. Europe / Japan. Scaled down to other countries by GDP<br><br>• Cost of level 2 retrofit is 78 € per $m^2$ in 2005 and 50 € per $m^2$ in 2030 in Europe, scaled down by geography |

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| **Retrofit HVAC, residential** | • When current gas/ oil furnaces or boilers expire, replace with the highest efficiency model, with AFUE (annual fuel utilization efficiency) rating above 95<br>• In appropriate climates, replace electric furnace with high efficiency electric heat pump<br>• When current air conditioning unit expires, replace with highest efficiency model (16 SEER or above)<br>• Reduce energy consumption from HVAC and AC through improved maintenance<br>– Improve duct insulation to reduce air leakage and proper channeling of heated and cooled air<br>– Ensure HVAC system is properly maintained, with correct level of refrigerant and new air filters | • For standard gas/ oil heaters, assume up to 19% savings potential from improved technology and proper sizing<br>• For electric heat pump, assume up to 50% savings potential compared to electric resistance heating. Savings is slightly lower in extreme climates<br>• For HVAC maintenance, assume total 15% savings from proper duct insulation and proper maintenance | • Assume 500 € premium for high efficiency gas/ oil model that covers 150 $m^2$ house; assume 2000 € premium for HE heat pump model that covers 150 $m^2$ house<br>• Assume 500 € premium for HE AC system<br>• Assume duct insulation/ maintenance job costs 635 € (aggressive cost estimate) to cover 150 $m^2$ house |
| **Retrofit water heating systems** | • When existing standard gas water heaters expire, replace with solar water heater, or with tankless/ condensing models<br>• When existing electric water heater expires, replace with solar water heater or electric heat pumps | • In developing countries, maximum solar capacity is installed by 2030. In developed countries, aim for 10% solar penetration, with remainder using most efficient technology (heat pump or HE gas) | • Solar water prices drop at 2.3% CAGR, based on historic improvement form 1984-2004 |
| **New and retrofit lighting systems** | • Replace incandescent bulbs with LEDs<br>• Replace CFLs with LEDs | • lumen/W varies by technology:<br>– Incandescent: 12<br>– CFL: 60<br>– LED: 75 in 2010; 150 by 2015<br>• In abatement case, assume full remaining share of incandescents switch to LEDs, and full remaining share of CFLs switch to LEDs | • Learning rate for LEDs based on historic 18% improvement in solar cell technology |

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| **New and "retrofit" appliances and electronics** | • Purchase high-efficiency consumer electronics (e.g., PC, TV, VCR/ DVD, home audio, set-top box, external power, charging supplies) instead of standard items<br>• When refrigerator/ freezer, washer / dryer, dishwasher, and fan expires, replace with high efficiency model | • HE consumer electronics use up to 38% less energy<br>• Package of certified appliances in developed countries consume ~35% less energy | • Electronics: 34 € price premium for small devices<br>• Appliances: price differential is 3-10% for HE devices |

## Buildings – Commercial

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **New build efficiency package (incl. insulation)** | • Reduce demand for energy consumption through improved building design and orientation<br>• Improve building insulation and airtightness; improve materials and construction of walls, roof, floor, and windows<br>• Ensure usage of high efficiency HVAC and water heating systems | • 61% savings potential on HVAC and water heating for new builds using "maximum technology" | • In developing regions, 5% cost premium on new builds with "high efficiency package." 4% premium in developed regions |
| **Insulation retrofit building envelope** | • Level 1 retrofit - "basic retrofit" package<br>– Improve building airtightness by sealing areas of potential air leakage<br>– Weather strip doors and windows | • Assume 48% savings potential in cold areas, and 11% savings potential in warm areas | • Level 1 retrofit is 4.10 € per $m^2$ in W. Europe/ Japan. Scaled down to other countries based on GDP |
| **Retrofit HVAC and HVAC controls** | • When HVAC system expires, install highest efficiency system<br>• Improve HVAC control systems to adjust for building occupancy and minimize re-cooling of air | • HVAC system retrofit: assume similar savings potential compared to residential (~15%)<br>• HVAC controls: 10-20% savings potential | • 500 € premium for every 5 tonnes (~17,000 W) of capacity installed<br>• 5,000 € cost for retrofit control system in 1,700 $m^2$ building in developed countries |
| **Retrofit water heating systems** | • When existing standard gas water heaters expire, replace with tankless gas, condensing gas, or solar water heater<br>• When existing electric water heater expires, replace with heat pump or solar water heater | • Assume that maximum solar capacity is installed by 2030<br>• No fuel shift, but shift to most efficient technology within fuel type (condensing gas or electric heat pump) | • Solar water heater learning rate based on 18% improvement in solar technology from 1950-2000 |

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| **New and retrofit lighting systems** | • Replace incandescent bulbs with LEDs<br>• Replace CFLs with LEDs<br>• Replace inefficient T12s/ T8s with new super T8s and T5s<br>• New build – install lighting control systems (dimmable ballasts, photo-sensors to optimize light for occupants in room)<br>• Retrofit – install lighting control systems (dimmable ballasts, photo-sensors to optimize light for occupants in room) | • In abatement case, assume full remaining share of incandescents switch to LEDS, and full remaining share of CFLs switch to LEDs<br>• Assume maximum switch from old T12 and T8s to new T8/T5s<br>• For lighting control systems<br>– Achieve 50% savings potential in new build<br>– Assume 29% savings potential in retrofit | • Learning rate for LEDs based on historic 18% improvement in solar cell technology<br>• Cost of labor and materials for new build 3.42 € per $m^2$. Cost for retrofit is 10.93 € per $m^2$ |
| **New and "retrofit" appliances and electronics** | • When existing standard gas water heaters expire, replace with tankless gas, condensing gas, or solar water heater<br>• When existing electric water heater expires, replace with heat pump or solar water heater | • 48% savings potential in office electronics<br>• 17% savings potential in commercial refrigerators | • 1.5 € price premium per item for high efficiency charging devices and reduction in standby loss<br>• 19 € premium for every 0.65 $m^2$ of high-efficiency refrigeration area |

## Waste

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **Flaring of landfill gas** | • Burn captured landfill gas to prevent methane from entering the atmosphere | • Flaring is assumed to cover the landfills remaining after the implementation of all other cheaper landfill gas reduction lever<br>• Capture rates over the lifetime of the landfill is assumed to be 75% | • Capex: € 50 to 71 per $tCO_2e$ of abatement capacity<br>• Opex: range from € 0.3 to 11 per $tCO_2e$ |
| **Electricity generation from landfill gas** | • Capture landfill gas to generate electricity | • LFG electricity generation is limited to a technical potential of 80% of all sites<br>• Capture rates over the lifetime of the landfill is assumed to be 75% | • Capex: € 281 to 402 per $tCO_2e$ of abatement capacity<br>• Opex: range from € 1 to 26 per $tCO_2e$<br>• Revenues from energy sales: range from € 42 to 55 per $tCO_2e$ |
| **Direct gas use of landfill gas** | • Capture landfill gas and sell to a captive player | • LFG direct use is limited to a technical potential of 30% of all sites<br>• Capture rates over the lifetime of the landfill is assumed to be 75% | • Capex: € 84 to 120 per $tCO_2e$ of abatement capacity<br>• Opex: range from € 0.2 to 10 per $tCO_2e$<br>• Revenues from energy sales: range from € 37 to 51 per $tCO_2e$ |
| **Composting** | • Produce compost through biological process where organic waste biodegrades | • Food: 1.0 $tCO_2e$ per ton<br>• Yard trimming: 1.3 CO2e per ton<br>• Paper: 1.9 $CO_2e$ per ton<br>• Wood: 1.5 $CO_2e$ per ton<br>• Textiles: 1.2 $CO_2e$ per ton | • Capex for composting per tonne of organic waste processed: € 34 to 49 per $tCO_2e$<br>• Opex for composting per tonne of organic waste : € 13 per $tCO_2e$<br>• Revenue from composting per tonne of organic waste : € 16 per $tCO_2e$ |
| **Recycling** | • Recycle raw materials (e.g., metals, paper) for use as inputs in new production | • Paper: 2.9 $tCO_2e$ per ton<br>• Cardboard: 3.7 $tCO_2e$ per ton<br>• Plastic: 1.8 $tCO_2e$ per ton<br>• Glass: 0.4 $tCO_2e$ per ton<br>• Steel: 1.8 $tCO_2e$ per ton<br>• Aluminium: 13.6 $tCO_2e$ per ton | • Capex for Recycling per tonne of waste processed: € 9 to 13 per $tCO_2e$<br>• Opex for recycling per tonne of waste : € 5 per $tCO_2e$<br>• Revenues from recycling :<br>– Paper: € 33 per $tCO_2e$<br>– Cardboard: € 67 per $tCO_2e$<br>– Plastic: € 67 per $tCO_2e$<br>– Glass: € 7 per $tCO_2e$<br>– Steel: € 13 per $tCO_2e$<br>– Aluminium: € 133 per $tCO_2e$ |

## Forestry

| Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|
| **Avoided deforestation from slash and burn agriculture** | • Reduction of emissions due to deforestation from slash and burn and other from of subsistence agriculture through compensation payments and income support to the rural poor and forest people | • Allocation of total deforestation emissions to Slash and Burn is 44% in Asia, 53% in Africa, 31% in Latin America<br>• Emissions per ha are 70% of biomass and dead wood pools and 15% of soil carbon | • Households deforest 2 ha per yr in Latin America and Asia, 1.5 ha per yr in Africa<br>• Payment to household $ 1,200 per yr for Brazil (WHRC study) – payments in other regions scaled on annual income of bottom 20% of population |
| **Avoided deforestation from cattle ranching** | • Reduction of emissions due deforestation from conversion to pastureland and cattle ranching through compensation of landholders for the lost revenue from one-time timber extraction and future cashflow from ranching | • Allocation of total deforestation emissions to Cattle Ranching is: 6% in Asia, 1% in Africa, 65% in Latin America<br>• Emissions per ha are 100% of biomass and dead wood pools and 15% of soil carbon | • Ranching profits are $ 15 per ha yr in Brazil, other regions assumed at constant margin<br>• Timber extraction is 70% of standing merchantable volume |
| **Avoided deforestation from intensive agriculture** | • Reduction of emissions due to deforestation from conversion to intensive agriculture through compensation of landholders for the lost revenue from one time timber extraction and future cashflow from agriculture<br>• Reference crops are soybean for South America and palm oil for Asia and Africa | • Allocation of total deforestation emissions to Intensive Agriculture is: 44% in Asia, 35% in Africa, 1% in Latin America<br>• Emissions per ha are 100% of biomass and dead wood pools and 50% of soil carbon | • Intensive agriculture PVs at 4% discount rate are $ 3–5,000 per ha per yr for soy, $15–17,000 per ha for palm oil<br>• Timber extraction is 100% of standing merchantable volume |
| **Avoided deforestation from timber extraction** | • Reduction of emissions from deforestation due to unsustainable timber extraction through compensation to landholders for lost timber revenue | • Allocation of total deforestation emissions to timber<br>• Extraction is: 6% in Asia, 10% in Africa, 3% in Latin America<br>• Emissions per ha are 30% of biomass pools, 10% of deadwood and litter pool, and 0% of soil carbon | • Timber extraction removes 15% of standing merchantable volume |

<table>
<tr>
<td>Aforestation of marginal croplands and pastureland</td>
<td>• Plantation of forest carbon sinks over marginal pastureland and marginal cropland<br>• Carbon is sequestered in the forest carbon pools<br>• Based on a “carbon graveyard” forest case, where forests are not harvested</td>
<td rowspan="2">• Available area excludes released or fallow croplands allocated to bioenergy<br>• Sequestration rates per ha are based on Moulton and Richards US estimates scaled on regional MAI for long range forestation</td>
<td rowspan="2">• Annual rental for crop and pasture lands is based on regional averages – degraded land is assumed not needing rental<br>• One-time capex and annual management costs are based on US estimates<br>• Payments are matched to carbon flux assuming full repayment of capex and PV of annual expenditure over 50 years of constant sequestration</td>
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<tr>
<td>Reforestation of degraded land</td>
<td>• Plantation of forest carbon sinks over degraded land with no food or feed production value<br>• Carbon is sequestered in the forest carbon pools<br>• Based on a “carbon graveyard” forest case, where forests are not harvested</td>
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<td>Forest management</td>
<td>• Increase of the carbon stock of existing forests based on active or passive management options such as fertilization, fencing to restrict grazing, fire suppression, and improved forest regeneration</td>
<td>• Total opportunity based on Moulton and Richard US estimate and scaled on total forest area<br>• Sequestration rates per ha are based on Moulton and Richards US estimates scaled on regional MAI for long range forestation</td>
<td>• One-time and annual costs based on<br>• US estimates[1]</td>
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</table>

1 Except that for Canada, where it is based on volume estimates from Chen et al. and IPCC estimates of fertilization costs at $ 20 per $tCO_2$

## Agriculture

| | Lever | Description | Key volume assumptions | Key cost assumptions |
|---|---|---|---|---|
| **Cropland management** | 1. Conservation tillage/residue management | • Reduced tillage of the ground and reduced residue removal/ burning | 0.2 to 0.7 $tCO_2e$/ha/yr | € -116 to -1/ ha/yr |
| | 2. Improved agronomy practices | • Improved productivity and crop varieties; extended crop rotations and reduced unplanted fallow; less intensive cropping systems; extended use of cover crops | 0.4 to 1.0 $tCO_2e$/ha/yr | € 8 to 17/ ha/yr |
| | 3. Improved nutrient management | • Adjusting application rates, using slow-release fertilizer forms or nitrification inhibitors, improved timing, placing the nitrogen more precisely | 0.3 to 0.6 $tCO_2e$/ha/yr | € -146 to -17/ha/yr |
| | 4.1. Improved rice management practices | • Mid-season and shallow flooding drainage to avoid anaerobic conditions | 4.0 to 4.9 $tCO_2e$/ha/yr | € -5 to 8/ ha/yr |
| | 4.2. Improved rice nutrient management practices | • Use of sulfate fertilizer instead of traditional nitrogen fertilizer | 1.2 to 1.5 $tCO_2e$/ha/yr | € -122 to 19/ha/yr |
| **Grassland** | 5. Improved grassland management practices | • Increased grazing intensity, increased productivity (excluding fertilization), irrigating grasslands, fire management and species introduction | 0.1 to 0.8 $tCO_2e$/ha/yr | € 2 to 4/ ha/yr |
| | 6. Improved grassland nutrient management practices | • More accurate nutrient additions: practices that tailor nutrient additions to plant uptake, such as for croplands<br>• Increased productivity (through better fertilization) For instance, alleviating nutrient deficiencies by fertilizer or organic amendments increases plant litter returns and, hence, soil carbon storage | 0.3 to 0.6 $tCO_2e$/ha/yr | € -146 to -17/ha/yr |

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| **Land restoration** | 7. Organic soils restoration | • To be used for agriculture, these soils with high organic content are drained, which favors decomposition and therefore, high $CO_2$ and $N_2O$ fluxes. The most important mitigation practice is to avoid the drainage of these soils or to re-establish a high water table | 33.5 to 70.2 $tCO_2e$/ha/yr | € 227/ha/yr |
| | 8. Degraded land restoration | • Land degraded by excessive disturbance, erosion, organic matter loss, Stalinization, acidification, etc. Abatement practices include re-vegetation (e.g., planting grasses); improving fertility by nutrient amendments; applying organic substrates such as manures, biosolids, and composts; reducing tillage and retaining crop residues; and conserving water | 3.4 to 4.4 $tCO_2e$/ha/yr | € 33/ha/yr |
| **Livestock management** | 9. Increased use of livestock feed supplements | • Livestock are important sources of methane, accounting for about one-third of emissions mostly through enteric fermentation | 8% to 15% | € 14 to 79 per $tCO_2e$ |
| | 10. Use of livestock enteric fermentation vaccines | • The key lever is the potential use of wide range of specific agents or dietary additives, mostly aimed at suppressing methanogenesis. The ones modeled are<br>• Propionate precursors which reduce methane formation by acting as alternative hydrogen acceptors. But as response is elicited only at high doses, propionate precursors are, therefore, quite expensive<br>– Vaccines against methanogenic bacteria which are being developed although not yet available commercially | 10% to 15% | € -128 to 65 per $tCO_2e$ |

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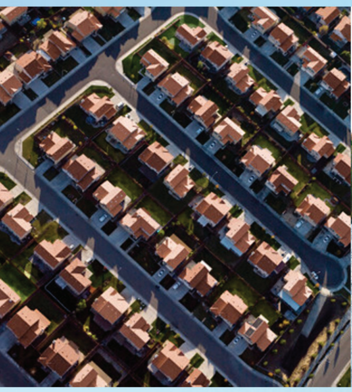

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