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Potentials and costs of carbon dioxide mitigation in the world's buildings

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Abstract

Buildings are responsible for over a third of global energy-related carbon dioxide (CO_2) emissions. A significant share of these emissions can be avoided cost effectively through improved energy efficiency, while providing the same or higher level of energy services. How large is this emission reduction potential globally and how much will it cost for society to unlock it? This paper provides answers to these questions, presenting the results of bottom-up research conducted for the Intergovernmental Panel on Climate Change (IPCC), based on the assessment of 80 country- or regional-level mitigation studies throughout the world. First, the paper analyses the findings of these studies in a common framework. Then, it aggregates their results into a global estimate of CO_2 mitigation potential. The paper concludes that by 2020 it is possible to cut cost effectively approximately 29% of buildings-related global CO_2 emissions, the largest among all sectors reported by the IPCC, representing a 3.2 $GtCO_2$eq. reduction. Developing countries house the largest cost-effective potential with up to 52% of building-level emissions, whereas transition economies and industrialised countries have cost-effective potentials of up to 37% and 25%, respectively. Energy-efficient lighting was identified as the most attractive measure worldwide, in terms of both reduction potential and cost effectiveness. If this potential is realised, the building-related CO_2 emissions would stay constant over 2004–2030. These stabilisation levels (if achieved by all other sectors) would cancel about 3°C temperature increase over the projected period of time.

Keywords: Greenhouse gas mitigation potential; Buildings; Energy efficiency

1. Introduction

A large body of literature suggests that the buildings sector is key for low-cost climate mitigation worldwide (IEA, 2006a; UNEP, 2007; IPCC, 2007). Above all, this sector is the second largest global carbon dioxide (CO_2) emitter after industry, representing approximately 33% of the global total (Price et al., 2006). At the same time, buildings are often considered as a "goldmine" of greenhouse gas (GHG) mitigation (Turmes, 2005) due to the large cost-effective opportunities as well as the broad variety of co-benefits. A wide range of best practices and cases demonstrate energy savings in buildings as high as 80% at little or no extra cost (Harvey, 2006; Öhlinger, 2006).

While many experts report such generous opportunities to conserve energy and to mitigate GHG emissions within the buildings of many countries, these opportunities are often not taken advantage of and not covered well by existing policies (Lechtenböhmer and Thomas, 2003). The reasons for this include the widespread and fragmented nature of the efficiency potential among buildings and among end-users (Novikova et al., 2006), combined with the especially high number and strong barriers to adopting efficient building technologies and practices (IEA, 2006a; IPCC, 2007; Golove and Eto, 1996). However, a large number of policy success stories and much experience, including the Energy Star endorsement program in the United States and the appliance labelling scheme in the European Union, have demonstrated that with well-designed policies aimed at saving energy major reductions

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in GHG emissions are possible (Ürge-Vorsatz et al., 2007a, b).

Therefore, if targeted by well-tailored policies, a significant portion of GHG emissions associated with buildings can be cut in a cost-effective way. However, how large is this potential and how much will it cost to capture it? How much can the world's buildings contribute to global mitigation efforts? How much will it cost to achieve a certain reduction target, or, vice versa, how much emissions can we reduce at an affordable cost? How do buildings compare to other sectors? What kind of mitigation options are of the highest priority and how do these priorities vary among different world regions? According to the knowledge of the authors and of a broad circle of experts in the energy efficiency community, an in-depth global bottom-up assessment of the global GHG mitigation potential in buildings has not been made recently. Besides three pieces of work covering several countries or regions (ADB, 1998; Halsnæs, 1999; Shukla, 1995), the authors, after an extensive search, have located only one study (AIM, 2004) in the public domain that provides a global estimate, which, however, covered a limited number of technological options.

2. Aim, significance and structure of the paper

This paper aims to address the gap in knowledge outlined in the introduction by presenting the results of a research effort that appraises the global potential for CO_2 mitigation in the world's building sector. The research relied on existing national and regional bottom-up assessments, summarising their results in a global framework with a focus on CO_2 mitigation. The goals of the paper are to (i) provide an estimate for the global potential of CO_2 mitigation in the world's building sector; (ii) identify the most promising mitigation options in terms of cost effectiveness and magnitude of emission reduction, and how these differ by region; and (iii) present a few representative supply curves of carbon mitigation to illustrate the dynamics of the cost effectiveness of mitigation options in different world regions.

The paper first describes the research methodology in detail, highlighting the limitations of the assessment. Then, the paper presents the main findings of a selection of studies using a common framework in order to be able to present the CO_2 savings potential and most attractive measures in a comparable manner. These are presented for a selection of countries, as well as grouped by key world regions. Then, the paper constructs and compares eight supply curves of conserved CO_2 for selected countries to show the cost ranges of these options in different world regions. Finally, the paper aggregates the results of the studies into a global CO_2 emission baseline, and calculates emission mitigation potential estimates for buildings in 2020 for the globe and its key regions as a function of mitigation cost.

This 2-year research was initiated as a response to the gap in knowledge with regard to global mitigation opportunities in buildings identified during the work under the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The aim of the research was to assist the global and national policy-making community as well as researchers with guidelines for the design of mitigation actions, as well as in strategy and priority setting among the different sectors and within the building sector. On the national level, the research can also be useful for countries which lack detailed sectoral studies, and thus can transfer extrapolated experience from neighbouring countries with similar climatic and economic conditions.

3. The methodological framework

This section discusses the major methods applied and assumptions made to enable a comparative assessment of studies evaluating buildings-related CO_2 mitigation opportunities around the world and to construct the global estimate of CO_2 reduction potential in the world's buildings, along with associated costs. First, the section describes how studies with different analytical approaches and assumptions were selected. Since each study uses its own methodology, different parameters and ways to present its results, the following section details how "apples were compared to oranges", i.e. how the results of the different studies were converted into a common framework enabling a comparative analysis. Then, the methodology employed for the production of supply curves of mitigated CO_2 is presented. The following section outlines the construction of the global CO_2 emissions baseline. Finally, the last section elaborates how the results of the studies were aggregated into the regional and global potential estimates. While this section may seem excessively long and detailed, in the authors' experience it is crucial that there is a clear understanding of the assumptions made and the corresponding limitations and strengths of this work. While several pieces of important policy-supporting work has cited the results of this research (IPCC, 2007; Seoul Conference, 2006; Waide, 2006; Ürge-Vorsatz, 2006; and others), the methods used and assumptions made for this work have not been documented, nor the detailed results published—all compromising the validity and relevance of the uses made of its findings.

3.1. Collection and pre-selection of studies

There are two principal approaches to global bottom-up assessment of CO_2 mitigation potential. These are, first, an overall analysis of mitigation opportunities in buildings on the global level and, second, an assessment of related country- or region-based literature with a following aggregation of the results into global estimates. Since data and information are scarce for many world regions on the detailed CO_2 mitigation opportunities in buildings and on details of building stock (technology penetrations, usage, floorspace, technological efficiencies, etc.), the authors found only the second method feasible. The advantage of the second method is that the individual country (or regional) studies already collect and assess this information, and their authors have the insight that is often needed for an optimal assessment of the mitigation options, taking into account the intricacies of local climate, culture, customs, and special technological preferences.

Following the second approach, the aim was set to collect as many national and regional bottom-up CO_2 mitigation potential studies that contained estimates separately for the buildings sector (residential or commercial, or ideally both) as possible. After an extensive search in the public domain (including the internet, books, databases, statistical publications, and periodicals), roughly 40 studies were obtained. Since it was important to become as representative globally as possible, over 70 experts were contacted (from research institutes, consultancies, Governments, and non-governmental organisations) from around 30 countries to locate further studies on potentials and costs of CO_2 mitigation. In total, 80 pieces of research were identified. The authors believe that the majority of publicly available important studies in this field in the world were mapped.

As the next step, a database was developed characterising the studies and their results in a common framework, based on a number of important parameters and criteria. All studies were thoroughly reviewed and the relevant parameter values and characteristics were extracted and inserted into the database. The list of mitigation studies collected in the database is presented in Appendix A.

Since the assumptions used in the studies differ considerably, and their results were presented using different formats, it was not possible to report the findings directly in a common framework. Other studies had shortfalls, which led the authors to decide that they should be excluded from the analysis: for instance, if a very limited number of options or policies were considered, or a project-based approach was used.

As a following step, the authors attempted to eliminate large deviations in results of the studies due to different methodological assumptions to facilitate further analysis. In this process, those studies were selected whose assumptions fell into a pre-defined common range of certain criteria. The first criterion was the analytical approach applied by studies. In general, the models fall into four categories: top-down[1] and bottom-up models,[2] their hybrids,[3] and integrated assessment models (IAM).[4] Since only a bottom-up analysis provides a detailed technological assessment of mitigation options and associated costs, studies applying this method were selected (or hybrid models based on bottom-up analysis with specific elements of the top-down approach). One exception to this rule was the Asian-Pacific Integrated Model (AIM, 2004), which used an IAM, and whose results were possible to include in the analysis. Additional criteria applied for the selection of studies are described in the next section, integrated with the description of the analysis.

3.2. Analysis of studies in a common framework

Different studies considered different ranges of mitigation options and policies, applied different delineations of sectors in terms of, for instance, including or omitting supply side effects, as well as whether the entire buildings sector had been covered or only the residential or commercial one or another subcategory. They had different start and target years and applied various approaches to construct baseline scenarios, used different potential definitions, and calculated effects of different discount rates. In the following sections, each of these key assumptions and characteristics of the studies and how the authors handled these in the unified framework is discussed.

3.2.1. Potential types

Depending on the technical, economic and social feasibility of technological options and market barriers hindering their applications, the mitigation potential[5] estimates are often classified as technical, economic, or market potentials, depending on the assumptions used for their derivation (for instance, see Rufo, 2003). However, the definitions of even the same potential types varied from study to study in many cases. Hence, independent of how a study classified the potential, uniform definitions were used and a potential type assigned for the purposes of the further comparability analysis. These potential definitions were based on IPCC guidelines (Blok and Price, 2005) lately reflected in the IPCC Report, Chapter 2 (IPCC, 2007), and are explained in Box 1.

3.2.2. Selected options, mitigation scenarios and potentials

Different studies applied different combinations of mitigation options and different delineations of sectors in terms of including the indirect CO_2 reduction effects or measures through energy supply side options. Since the research was focused on demand-side mitigation, only CO_2

[1]Top-down models search for the market equilibrium brought by setting of carbon targets or introducing fiscal policy tools and assuming that firms behave by maximizing their profit. The assessment is typically performed through linear or non-linear systems of equations using aggregate economic indicators as variables.

[2]The bottom-up analysis intends to provide an overview of technological emission reduction options and costs of their implication.

[3]Hybrid models are derived from top-down models with bottom-up elements, or vice versa.

[4]Integrated assessment models (IAM) are typically the most complex and combine the interactions of economic and biophysical systems into the integrated system.

[5]These categories are similar to potential categories used in the energy-efficiency or renewable energy literature.

Box 1
Potential definitions as applied by the Fourth IPCC Assessment Report on Climate Change (IPCC, 2007)

The *technical potential* is defined as the amount by which it is possible to reduce GHG emissions by implementing already demonstrated technologies and practices without specific reference to costs although economic considerations might be applied.
The economic potential is a cost-effective potential for GHG mitigation when non-market social costs and benefits associated with mitigation options are considered with market costs and benefits using social discount rates instead of private ones at particular levels of carbon prices. However, since the majority of the studies reviewed in the paper were not able to include all social cost elements into consideration and did not take into account the carbon price, the *economic potential* for the purposes of the paper *was assumed as the cost-effective potential at zero social cost and zero carbon price*.
The *market potential* was defined as the amount of GHG mitigation occurring under forecast market conditions including policies and measures based on private unit costs and discount rates.

savings were filtered that resulted from the demand-side measures, leaving the supply-side improvements segregated. In a very few cases where such separation was impossible, but otherwise the study covered important regions/countries, provided important and high-quality results and no substitute was available, exceptions were made. This was the case for the studies covering EU-25, Germany, USA and Japan (Lechtenbohmer et al., 2005; Martinsen et al., 2002; Koomey et al., 2001; and Murakami et al., 2006, respectively). If studies considered policies (vs. technological options), they were segregated depending on what kind of effect—demand or supply side—they have (for instance, USA (Koomey et al., 2001) and Australia (Australian Greenhouse Office, 2005) studies).

Regarding the question how comprehensiveness of the range of applied technological measures investigated in studies was, it is important to highlight that many studies covered a limited number of measures or options. For instance, the Thailand study (ADB, 1998) included only three technological programs related to lights, refrigerators, and air-conditioners. Therefore, due to the limited number of technological options considered by studies, the real potential for that region/country is likely to be higher than the one reported in the paper.

Significant uncertainty in relation to the amount of available potential was also generated by studies which did not estimate the mitigation potential as it is but evaluated national mitigation strategies often aimed at specific aims and thus shrinking the scope of possible improvements. For example, the Indian country study (Reddy and Balachandra, 2005) examined a mitigation scenario accounting for emission reductions only due to opportunities offered by the Kyoto Protocol's clean development mechanism (CDM). The EURIMA report (Petersdroff et al., 2005) analysed the impact of the EU Directive on Energy Performance of Buildings concerning the heating-related CO_2 reduction potential and its cost effectiveness in the New EU Member States[6] in comparison to the frozen efficiency scenario. This is the second reason for interpretation of the figures in such analyses as low estimates of the real mitigation potential.

A third reason for why the mitigation potential figures are likely to be lower than the real potentials is the general shortcoming of the bottom-up assessment approach when the impact of separate measures is considered. The literature documents clearly (Harvey, 2006; IPCC, 2007) that integrated approaches to whole building construction and operation (also renovation, but for that case the effect is lower) result in substantially larger potential energy (and thus carbon) savings than a piecemeal approach; however, such integrational opportunities are difficult to capture in studies that aim to prioritise mitigation options and calculate their cost effectiveness.

As a result of these last three limitations (in the studies and in the approach), the resulting potential calculations in this study represent low estimates of the real potential, or likely underestimate the real potential.

3.2.3. Gas unification

Since the focus of the research was on CO_2 only, if a study covered all GHG gases, CO_2 mitigation potential was separated from the overall GHG potential, if possible, to make the input data coherent.

3.2.4. Baseline

The majority of the studies identified the mitigation potential as compared to a Business-As-Usual Scenario (BAU). However, there was a slight variation in definition of BAU scenarios which is impossible to eliminate. In a few cases, studies used a frozen efficiency scenario as a reference (namely AIM (2004); Joosen and Blok (2001); De Villiers and Matibe (2000); De Villiers (2000); and Mirasgedis et al. (2004)). No corrections were performed for such studies because the corresponding potential would also have had to be reduced, which was impossible to recalculate. As a solution to this problem, a global baseline was derived based on the studies covered, which is a

[6]The new European Union Member State considered wereHungary, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Poland, and the Czech Republic.

composite of the baselines used in them. This way each world region is represented by a baseline that is consistent with the mitigation options for that region. As a result the validity of the global potential is not compromised, since this baseline in calculating the global total was used for the regions applying a frozen efficiency baseline (see Section 3.4). Therefore, the global potential is consistent with the global baseline (i.e. measures that are considered in the potential calculations are not considered in the baseline, and vice versa).

Some studies did not report the baselines used at all. To calculate the potential as a percentage of the baseline for such studies, either the latest available National Communications to the United Nations Framework on Climate Change (NC UNFCCC) of these countries, or other recent climate reports containing such estimates were used. This is the case for Russia, UK, Poland, and Japan (the last for the case of aggregation only; for the comparative analysis, Murakami et al. (2006) was used).

3.2.5. Identifying options with lowest costs: cost analysis and discount rates

The cost effectiveness of mitigation options is very sensitive to the discount rate chosen for the analysis. Even small changes in the discount rate can affect the costs of future technology options, their relative preferences, and thus reverse the ranking of technological options. For instance, AIM (2004) used 5%, as well as 33% to highlight high investment risk for energy efficiency equipment in the residential sector. The result of the reduction potential for the 5% discount rate was 255 million tons higher than that for the second one (at the negative mitigation cost). Balancing the aim to minimise the differences in results due to different discount rates and the aim of including as many studies as possible to make a global estimate more thoroughly founded, those studies were selected for further analysis which had an analysis using a discount rate within the interval of 3–10%.[7]

Studies often reported mitigation costs in their national currencies for different years. All currencies were converted into US\$2000 using GDP Deflators IMF (International Monetary Fund, 2004) and exchange rates from IEA (2004), Bank of England online (2005), and Taiwan Department of Investment Services online (2005). Many studies did not specify the year of a currency; for this parameter the year of their publication was assumed.

3.2.6. Projection period

The majority of collected studies had a target year of 2020; however, some of them had other target years, mainly between 2010 and 2030. If a year after 2020 was targeted, figures for 2020 were derived by interpolating these longer-term projections for 2020 (for instance, the UK baseline). Under the base year parameter, studies also understood different things (for instance, the base year of currencies or the start year of projected CO_2 emissions). For assessment purposes, starting the application of mitigation options was assumed under the base year.

3.2.7. Individual assumptions for developed case studies used in the cross-national potential comparison

The above-described calculations, which were made through each of the individual profiles created of the

Table 1
Individual assumption and calculations performed for selected key reviewed studies

N	Country/reference	Operations/assumptions
1	UK (DEFRA, 2006)	• For the commercial sector—no mitigation costs, splitting of the potential for this sector into costs was omitted • For the residential sector: costs were converted from pounds/ton of carbon into US\$2000/tCO_2 • Missing baseline was taken from Johnston et al. (2005), tracing intermediate 2020 projections of BAU in the study
2	EU-15 (Joosen and Blok, 2001)	• Costs were converted from EUR/tCO_2 into US\$/tCO_2 • Target year of 2010 was projected to 2020 for global aggregation (see Section 3.5) • Frozen efficiency baseline was used by the study and accepted for further analysis without revision
3	South Africa (De Villiers, 2000; De Villiers and Matibe, 2000)	• Costs were converted costs from Rands1997/tCO_2 (1997 assumed by authors) into US\$2000 costs • Frozen efficiency baseline was poorly reported (probably with mistakes); the baseline was estimated by the authors based on data given by other reports or own assumptions where no data were located • Potential was given over a 30-year period and was recalculated in 2030 applying linear extrapolation (assuming linear growth of the baseline and the potential) • Since the potential was likely underestimated, its projection in 2020 was accepted at the same level as in 2030
4	Ecuador (FEDEMA, 1999)	• Costs were converted from US\$1999/tCO_2 into US\$ 2000/tCO_2 • Target year was 2030 and the potential was interpolated to 2020 assuming its exponential growth over the projection period for the global calculations
5	Botswana (MMEWA, 1999)	• Costs were converted from Botswana Pula 1999/tCO_2 into US\$ 2000/tCO_2 • The buildings baseline given in the study appeared higher than the potential (poor reportage of the study), which is why the potential as the share of the national

[7]This also corresponded with the IPCC calculation guidelines (Blok and Price, 2005).

Table 1 (*continued*)

N	Country/reference	Operations/assumptions
		baseline was not reported (no other study was located to report the building-level baseline)
6	Hungary (Szlavik et al., 1999)	• The study targeted 2030; therefore the potential was interpolated to 2020 for the global aggregation assuming the exponential growth of the baseline and the potential over the projection period • Costs were converted from Hungarian Forints 1999 into US$2000 • Supply-side options were disaggregated and excluded • The study reported the costs only for several selected options; mitigation options were aggregated into categories which contained at least one option for which the costs are reported and these costs were applied for the whole category
7	South Korea (ADB, 1998)	• Costs were converted from US$1995 into US$2000
8	Thailand (ADB, 1998)	• Costs were converted from US$1995 into US$2000 • Only the residential potential was reported because the potential for the commercial sector appeared higher than its baseline, it is likely that there is a mistake in the study
9	Pakistan (ADB, 1998)	• Costs were converted from US$ 1999 into US$ 2000
10	APEIS study (AIM, 2004)	• A study covered all countries and regions; used limited number of options and frozen efficiency baseline, therefore several countries were taken from it only if there was a lack of the coverage of these countries or regions from other studies
11	Canada (Jaccard and Associates, 2002)	• The missing baseline was taken from Jaccard and Associated (2000) • Target year was 2010, therefore the potential to 2020 for aggregation was estimated assuming the exponential growth of the baseline and the potential over the projection period (see Section 3.5) • Costs were converted from US$1995 into US$ 2000 • Only capital costs were reported, not taking into account the energy price
12	Croatia (1NC UNFCCC, 2001)	• The base year for application of measures and the discount rate applied to the analysis were not reported
13	Russia (Izrael et al., 1999)	• Missing national baseline was estimated based on the Russian UNFCCC 3NC (low-efficiency scenario). The share of the residential and commercial sectors in the national baseline for heat-related emissions (11%) was taken from the National Inventory (Inter-Agency Climate Change Commission of the Russian Federation, 2002), and the share of 11% for the residential and commercial emissions associated with electricity consumption is taken from information on OPEC online (2006)
14	India (Reddy and Balachandra, 2005)	• The potential and the base year emissions given in the study included emissions from fuelwood burning, which were excluded (because it is carbon-neutral), and which corresponds to the data presented in the Indian National Communication • Emissions in the base and target years were missing and are thus estimated by the authors based on energy consumption and CO_2 changes over the projected period, and primary and final fuel mixes • The target year was 2010, the baseline and the potential were projected to 2020 for the global aggregation assuming their exponential growth (Section 3.5)
15	Poland (Gaj and Sadowski, 1997)	• Costs were converted from US$1997 into US$2000 • The missing baseline was taken from the Polish 3NC UNFCCC

study, aimed at making the studies comparable within the common framework and usable for further global aggregation that will be described below. The assumptions applied individually from study to study are presented in Table 1.

The results of the comparative analysis based on the methodology discussed in this section (Section 3.2) are presented in Chapter 4 of the paper.

3.3. Development of supply curves of conserved CO_2 and ranking mitigation options

From a policy-making perspective it is important to identify the priority of mitigation options according to the amount of potential they can tap, as well as according to their costs. The method of supply curves of mitigated CO_2 represents a convenient tool for such analysis. CO_2 mitigation supply curves characterise the potential savings which result from a set of climate mitigation measures as a function of the cost per unit of CO_2 (Sathaye and Meyers, 1995). Initially this method has been developed as an analogue to supply curves for commodities used in the economic literature.

However, since the construction of such curves is very data intensive, it was only possible to generate them for eight studies that provided sufficient detail (based on

Joosen and Blok, 2001; ADB, 1998; De Villiers and Matibe, 2000; De Villiers, 2000; Szlavik et al., 1999; DEFRA, 2006; Mirasgedis et al., 2004; Gaj and Sadowski, 1997). Only these studies reported, among other things, the potential in the target year, associated individual measures, buildings baseline emissions, and the associated mitigation costs accurately. The discussion of supply curve comparisons is presented in Chapter 5 of the paper.

3.4. Construction of global baseline CO_2 emission projections

There are several CO_2 emission baseline projections which have been developed recently. The most broadly used are the World Energy Outlook scenario (IEA, 2006b) and A1B and B2 of the Special Report on Emission Scenarios (IPCC, 2000), the emission scenarios used by the IPCC (Price et al., 2006).[8] However, for the purpose of our analysis, the aggregated baselines of the reviewed studies were used, i.e. not other exogenous scenarios, due to the aforementioned reasons—to ensure the highest possible consistency of the baseline with the mitigation measures. This is because the exogenous projections are based on their own storylines and general macroeconomic and social descriptions of the future, which make it impossible to know what kinds of mitigation measures are already considered in these baselines. Additionally, some of these scenario baseline assumptions, such as the rates of economic development, differ significantly from those in the collected studies.

For the purposes of construction of baseline CO_2 emissions over the period of 2000–2020, the world was split into seven regions with similar economic and climate conditions.[9] For each region, two to four studies were located, thus dividing each region into two to four subregions represented by these marker countries in terms of emission growth rates and potential as a percentage of the baseline. Since few studies reported the potential as a function of cost, as is required for further analysis, it was possible to use only 17 studies[10] from the remaining subset that met our other selection criteria. Also, not all of these 17 studies reported carefully the baseline emissions. For those studies which failed to do so, the baseline emissions were borrowed from other studies,[11] as described in Section 3.2.4.

The majority of the studies reported their baseline emissions over the period 2000–2020 (in dynamics or spot figures), except for seven of them.[12] For these countries/regions, it was assumed that the emission growth rates are the same over the 2000–2010 period as for 2010–2020.

For each country/region the exponential growth rates of CO_2 baseline emissions were calculated as

$$R_{\text{exponential}} = \text{EXP}\left(\frac{1}{20}\,\text{LN}\,\frac{\text{Emissions}_{\text{target year}}}{\text{Emissions}_{\text{base year}}}\right) - 1. \qquad (1)$$

The growth of CO_2 baseline emissions in countries for which it was possible to estimate the exponential growth with the formula above was assumed to be the same as that in surrounding countries with similar climate and economic conditions. Thus, it was deduced that each of the seven global regions consists of two to seven subregions for which the exponential growth rates of CO_2 baseline emissions are estimated. To estimate CO_2 baseline growth rates for each of the seven world regions, the population-weighted average CO_2 baseline growth rates of the two to four subregions were calculated.

The baseline emissions over the 2000–2020 period were constructed using the figures of CO_2 baseline emissions according to the IPCC SRES A1B and B2 data in 2000 as the start year and applying the calculated growth rates. Assuming that the emission growth rates over the 2020–2030 period will be the same as for the 2000–2020 period, these trends were extrapolated for the period 2020–2030. The regional baseline projections were aggregated according to three country groups: developed countries, economies in transition, and developing countries, and then, consequently, into the global baseline projections.

In relation to WEO 2006, and the IPCC SRES A1B and B2 baseline scenarios, our baseline lay higher than WEO and B2, but lower than the A1B scenario. The baseline did not go out of the baseline corridor created by SRES and WEO scenarios from 2000 to 2030. This is in harmony with our knowledge about these baselines: the created baseline is likely to be higher than the WEO 2006 projections since it included a few frozen efficiency baselines, and therefore should be higher than a business-as-usual forecast. Since

[8] Price et al. (2006) considered two scenarios from the IPCC Special Report on Emission Scenarios (SRES) for decomposing future CO_2 emissions to the sectoral level, A1B and B2 scenarios. The B2 world is one of increased concern for environmental and social sustainability compared to the A1 storyline, which is a case of rapid and successful economic development.

[9] These were OECD North America, OECD Pacific, Western Europe, Transition Economies, Latin America, Africa and Middle East, and Asia.

[10] AIM, 2004; ADB, 1998 (two studies); De Villiers and Matibe, 2000; De Villiers, 2000; ERI, 2004; Joosen and Blok, 2001; Koomey et al., 2001; Lechtenbohmer et al., 2005; Australian Greenhouse Office, 2005; Martinsen et al., 2002; DEFRA, 2006; Jaccard and Associates, 2002; Izrael et al., 1999; Reddy and Balachandra, 2005; FEDEMA, 1999; and estimates of the Japanese research group under the leadership of Dr. Hiroshi Yoshino based on Flat Glass Manufactures Association of Japan, 2006; Government of Japan, Cabinet Office, 2005; Tanakaa et al., 2006; Nishioka, 2001; Sadohara et al., 1998.

[11] Interlaboratory Working Group, 1997; Jaccards and Associated, 2000; Johnston et al., 2005; Polish UNFCCC NC3; Japanese UNFCCC NC4; Russian UNFCCC NC3.

[12] The Interlaboratory Working Group (1997), which reported emissions over 1997–2010 for USA, Jaccards and Associated (2000), which reported 2000–2010 for Canada; the Japanese UNFCCC NC4, which reported 2002–2010 for Japan; Joosen and Blok (2001), which reported 1990–2010 for EU-15; De Villiers (2000) and De Villiers and Matibe (2000), which reported 1990–2030 for South Africa, Reddy and Balachandra (2005), which reported 2000–2010 for India, and FEDEMA (1999), which reported 2000–2030 for Ecuador.

three out of the 17 studies used a frozen efficiency baseline (see Section 3.2.4), the baseline developed can be considered a business-as-usual one with some frozen efficiency elements.

3.5. Construction of the global estimate for CO_2 mitigation potential in cost categories

3.5.1. Selected studies for their aggregation into the global potential numbers

As documented above, estimates of the potential for CO_2 emission reductions in different world regions were developed on the basis of 17 studies covering five continents. As already mentioned, all studies included demand-side measures only, except for the USA, the EU-25 and the German studies[13] (Koomey et al., 2001; Lechtenbohmer et al., 2005; Martinsen et al., 2002). However, inclusion of these studies does not affect much the overall global estimate. The dominating focus of the US study was demand-side measures with only a couple of supply-side measures. The results of the EU-25 studies were applied to only a limited number of countries in the CEE region, whereas the results of the German study were applied only to Germany and were not extrapolated to other countries.

3.5.2. The estimate of the global potential as the baseline share

The global potential estimates as a percentage of the baseline emissions are based on the individual country profiles described in Section 3.2.7. For this purpose, the potentials from the individual measures reported in the profiles were summarised into three cost categories: below 0 US\$/tCO_2 (net negative costs), 0–20 US\$/tCO_2, and 20–100 US\$/tCO_2. Analogously with the baseline construction, the CO_2 potentials as percentages of the baseline in the respective cost categories were calculated using the method of a population-weighted average potential in the subregions for each cost category, and for each of the seven world regions.

There were three additional challenges faced during the global aggregation. First, some studies reported the potential for 2010 while the global estimates are for 2020. For such cases, these figures were extrapolated to the year 2020 applying Formula (2) below. This was the case for Canada, Japan, EU-15, Russia, and India (Joosen and Blok, 2001; Jaccard and Associates, 2002; Izrael et al., 1999; Reddy and Balachandra, 2005; and estimates of the Japanese research group based on Flat Glass Manufactures Association of Japan, 2006; Government of Japan, Cabinet Office, 2005; Tanakaa et al., 2006; Nishioka, 2001; Sadohara et al., 1998). Formula (3), which is the inverse of Formula (2), was applied to Ecuador (FEDEMA, 1999) reporting a 2030 target year. The potential figures for South Africa in 2030 were likely underestimated and were thus kept constant for the year 2020:

$$\text{Potential}_{2020} = 1 - (1 - \text{Potential}_{2010})^{20/10}, \qquad (2)$$

where the year 2000 is assumed as the start year.

The formula used for interpolating the potential from target year 2030 to 2020 was

$$\text{Potential}_{2020} = 1 - (1 - \text{Potential}_{2030})^{20/30}. \qquad (3)$$

Another challenge was that some studies only reported the potential for the residential sector. For such cases, the assumption was made that the potential (as well as baseline growth rates) for the whole buildings stock would be the same as for the residences (for studies of Reddy and Balachandra, 2005; AIM, 2004; Martinsen et al., 2002; DEFRA, 2006).

Thirdly, in three cases the potential was not split into cost categories by studies; so it was done by the authors for the purposes of the present paper. There was, firstly, the German technical potential (Martinsen et al., 2002), which was split according to the cost distribution of the EU-15. Secondly, costs for the Russian potential (Izrael et al., 1999) were distributed according to the cost distribution found, like the population-weighted average of the Hungarian and Polish potentials that were considered to be the closest to Russian conditions. Thirdly, the costs for the Chinese potential were distributed like those of the Pakistani potential.

3.5.3. Estimate of the global potential in absolute values

The absolute values of the potential were aggregated into three country groups: developed countries, economies in transition, and developing countries. Then, the obtained absolute figures of the potential for three country groups were divided by the respective baselines to derive the potential of country groups as a baseline percentage.

3.5.4. Split of the potential into fuel- and electricity-associated savings

In order to avoid double counting of the potential among the energy production and end-use sectors, end-use sector potential needed to be split into those for electric end-uses and fuel-related end-uses. Since a very limited number of studies reported baseline CO_2 emissions per fuel used, it was not possible to make a split solely based on studies. To make such a split of the baseline, first of all, for each country group (developed countries, economies in transition, and developing countries), marker countries were selected which have studies reporting the structures of their CO_2 emissions. Then, the structures of these marker countries were compared to the split of CO_2 emissions into electricity and fuel sources reported by WEO, A1 and B2 IPCC SRES scenarios. For each country group, WEO, A1 or B2 scenario, whichever structure in the target year was the closest to that of the marker country was selected and

[13] Murakami et al. 2006 considered both demand-side and supply-side options and thus was used for the comparative analysis, while for the purpose of the global aggregation instead the estimates of the Japanese research group were used.

the country group baseline was split according to the selected scenario.

The split of the potential was performed based on developed individual country profiles (Section 3.2.7). While developing these profiles, each individual option was associated with fuel or electric savings. Then, the average structure of CO_2 mitigation potential in each cost category in each country group was calculated based on those studies which allow such reporting. Having received the structure of the potential in cost categories for the country groups, these structures were applied to the potentials as a percentage of the baseline in each world region. Then, related absolute potential figures were calculated and divided by the baseline fuel- and electricity-associated savings. The overall results of the global potential aggregation and its split into fuel- and electricity-associated savings are presented in Chapter 6 of the paper.

4. Results: comparative analysis of CO_2 reduction potential in buildings in selected countries

As shown in the previous section, various approaches have been used to estimate the costs of CO_2 mitigation in buildings. In many cases, the results of different studies even for the same country vary considerably, depending on assumptions regarding base-case conditions; the diversity of the building stock and operating practices; the rate of technology diffusion; the shapes of cost, price, and learning curves; and the discount rate adopted for evaluating the various options. Despite these associated methodological challenges, a selected set of studies was analysed applying a common methodological framework as described in previous sections, whose aim was to overcome as much of these differences as possible. The detailed analysis is presented in Appendix B of the paper. Table 2 provides a short summary of the analysis and reports ranges of the estimates of different types of CO_2 mitigation potential in different world regions and countries, as well as ranks the most promising options in terms of the size of potential and its mitigation cost.

According to Table 2, estimates of technical potential range from 18% of CO_2 emissions in Pakistan (ADB, 1998), where only a limited number of options were considered, to 54% in 2010[14] in a Greek study (Mirasgedis et al., 2004) that covered a very comprehensive range of measures in the residential sector. The estimates of economic potential[15] vary from 12% in EU-15 in 2010[16] (Joosen and Blok, 2001) to 52% in Ecuador in 2030[17] (FEDEMA, 1999). Estimates of market potential range from 14% in Croatia, focusing on four options only (Croatia 1NC UNFCCC, 2001), to 37% in the USA, where a wide range of policies were appraised (Koomey et al., 2001).

The table attests that efficient lighting technologies are among the most promising measures in buildings, in terms of both cost effectiveness and size of potential savings in almost all countries. In developing countries, efficient stoves rank second, while the second-place measures differ in the industrialised countries by climatic and geographic region. Almost all studies examining economies in transition located typically in cooler climates have found heating-related measures to be the most cost effective, especially insulation of walls, roofs, windows, and floors, as well as improved heating controls for district heat. In developed countries, appliance-related measures are identified as the most cost effective, with cooling-related equipment upgrades ranking high in the warmer climates. Air-conditioning savings can be more expensive than other efficiency measures, but can still be cost effective because they tend to displace more expensive peak power. In terms of the size of savings, improved insulation and district heating in the colder climates and efficiency measures related to space conditioning in the warmer climates come first in almost all studies, along with cooking stoves in developing countries. Other measures that rank high in terms of savings potential are solar water heating, efficient lighting, and efficient appliances, as well as building energy management systems.

5. Results

5.1. International comparison of the cost dynamics for CO_2 limitation: supply curves of CO_2 mitigation

Fig. 1 illustrates the potential for CO_2 abatement as a function of costs for eight selected recent detailed studies from different world regions. The steepness of the curves, i.e. the rate at which the costs of the measures increase as more of the potential is captured, varies substantially by country and by study. Despite the concern about different assumptions made by different studies, the figure clearly demonstrates the wide range of opportunities for cost-effective and low-cost CO_2 mitigation in buildings in all world regions. The supply curves of developing countries in focus are characterised by a flat slope and lie, in general, lower than the curves of developed countries. The flat slope justifies the general perception that there is a higher abundance of "low-hanging fruit" in the developing world. More concretely, the net costs of GHG mitigation in buildings in these countries do not grow rapidly even over 30–50% of emissions reductions. For developed countries, the baseline scenario assumes that many of the low-cost

[14] If the app. formula of $\text{Potential}_{2020} = 1-(1-\text{Potential}_{2010})^{20/10}$ is used to extrapolate the potential as percentage of the baseline into the future (2000 is assumed as a start year), this will correspond to app. 78% CO_2 savings in 2020.

[15] In this chapter, we refer to "cost-effective" or "economic" potential, to remain consistent with the energy-efficiency literature, considering a zero carbon price.

[16] Corresponds to an app. 22% potential in 2020 if the extrapolation formula is used.

[17] Corresponds to an app. 38% potential in 2020 if the formula is applied to derive the intermediate potential.

Table 2
Greenhouse gas emissions reduction potential ranges for the buildings stock in 2020[a] by country groups

Economic region	Countries/country groups reviewed for region	Potential as % of national baseline for buildings[b]	Measures covering the largest potential	Measures providing the cheapest mitigation options
Developed countries	USA, EU-15, Canada, Greece, Australia, Republic of Korea, United Kingdom, Germany, Japan	Technical: 21–54%[c] Economic: 12–25%[d] Market: 15–37%	1. Shell retrofit, inc. insulation, esp. windows and walls 2. Space heating systems and standards for them 3. Efficient lights, esp. shift to CFLs and efficient ballasts	1. Appliances such as efficient TVs and peripheries (both on-mode and standby), refrigerators and freezers, followed by ventilators and air-conditioners 2. Water heating equipment 3. Lighting best practices
Economies in Transition	Hungary, Russia, Poland, Croatia, as a group: Latvia, Lithuania, Estonia, Slovakia, Slovenia, Hungary, Malta, Cyprus, Poland, the Czech Republic	Technical: 26–47%[e] Economic: 13–37%[f] Market: 14%	1. Pre- and post-insulation and replacement of building components, esp. windows 2. Efficient lighting, esp. shift to CFLs 3. Efficient appliances such as refrigerators and water heaters	1. Efficient lighting and its controls 2. Water and space heating control systems 3. Retrofit and replacement of building components, esp. windows
Developing countries	Myanmar, India, Indonesia, Argentine, Brazil, China, Ecuador, Thailand, Pakistan, South Africa	Technical: 18–41% Economic:13–52%[g] Market: 23%	1. Efficient lights, esp. shift to CFLs, light retrofit, and kerosene lamps 2. Various types of improved cook stoves, esp. biomass stoves, followed by LPG and kerosene stoves 3. Efficient appliances such as air-conditioners and refrigerators	1. Improved lights, esp. shift to CFLs, light retrofit, and efficient kerosene lamps 2. Various types of improved cook stoves, esp. biomass based, followed by kerosene stoves 3. Efficient electric appliances such as refrigerators and air-conditioners

[a]Except for EU-15, Greece, Canada, India, and Russia, for which the target year was 2010, and Hungary, Ecuador, and South Africa, for which the target was 2030.
[b]The fact that the market potential is higher than the economic potential for developed countries is explained by limitation of studies considering only one type of potential; so information for some studies likely having higher economic potential is missing.
[c]Both for 2010; if the approximate formula suggested in 3.5.2 is used to extrapolate the potential as a percentage of the baseline into the future (the year 2000 is assumed as a start year), this interval would be 38–79%.
[d]Both for 2010; if the suggested extrapolation formula is used, this interval would be 22–44%.
[e]The last figure is for 2010 corresponds to 72% in 2020 if the extrapolation formula is used.
[f]The first figure corresponds to 24% in 2020 if the extrapolation formula is used.
[g]The last figure is for 2030 corresponds to 38% in 2020 if the suggested extrapolation formula is applied to derive the intermediate potential.

opportunities are already captured due to progressive policies in place or in the pipeline. It is important to note that the curve with the steepest slope, the one for EU-15, is for 2010 rather than 2020. We estimate that for 2020 the cost effectiveness of the options becomes more favourable, and that this curve would also assume a flatter slope.

6. Estimates of CO_2 mitigation potential in the World's buildings

While there are methodological challenges in aggregating figures of the discussed studies based on differing assumptions, an estimate for the global potential in the buildings sector was developed correcting for as many of the differing assumptions as possible, as described in the methodology section (Section 3) above in detail. The results of the calculations suggest that by 2020, globally, approximately 29% of the projected baseline emissions can be avoided cost effectively through mitigation measures in the buildings sector. Additionally, at least 3% of baseline emissions can be avoided at costs of up to 20 US\$/tCO_2, and 4% more if costs up to 100 US\$/tCO_2 are considered. However, due to the numerous opportunities at low costs, the high-cost potential has been assessed to a limited extent in the vast majority of studies, and thus *this figure is an underestimate*. These estimates represent a reduction of approximately 3.2, 3.6, and 4.0 billion tons of CO_2eq. in 2020, at 0, 20 US\$/tCO_2, and 100 US\$/tCO_2, respectively, assuming the baseline developed on the basis of the reviewed studies. If the potential estimates are extrapolated

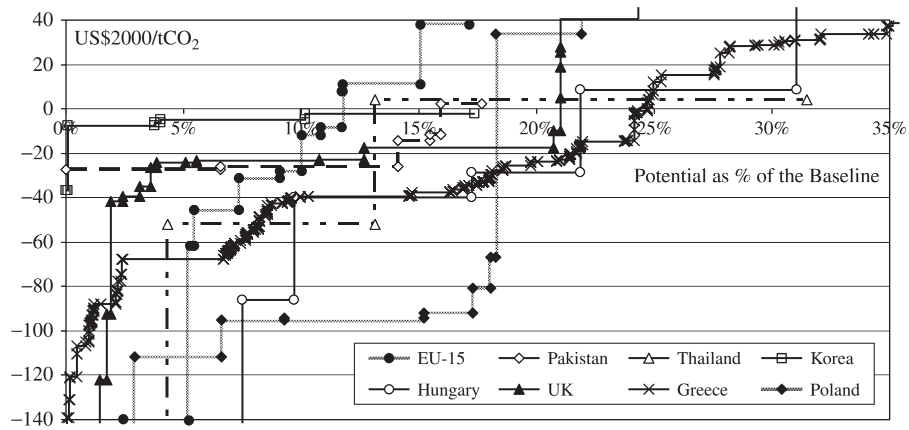


Fig. 1. Supply curves of conserved CO_2 for commercial and residential sector* in 2020** for different world regions. *Except for the UK, Thailand, and Greece, for which the supply curves are for the residential sector only. **Except for EU-15 and Greece, for which the target year is 2010, and Hungary, for which the target year is 2030. *Notes*: Each step on the curve represents a type of measure, such as improved lighting or added insulation. The length of a step on the "*X*" axis shows the abatement potential represented by the measure, while the cost of the measure is indicated by the value of the step on the "*Y*" axis. *Sources of data*: Joosen and Blok, 2001; ADB, 1998; De Villiers and Matibe, 2000; De Villiers, 2000; Szlavik et al., 1999; DEFRA, 2006; Mirasgedis et al., 2004; Gaj and Sadowski, 1997.

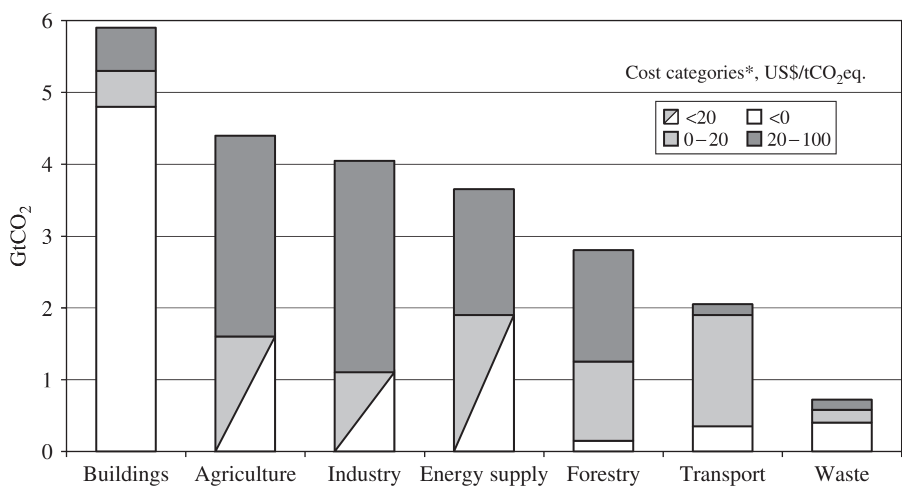
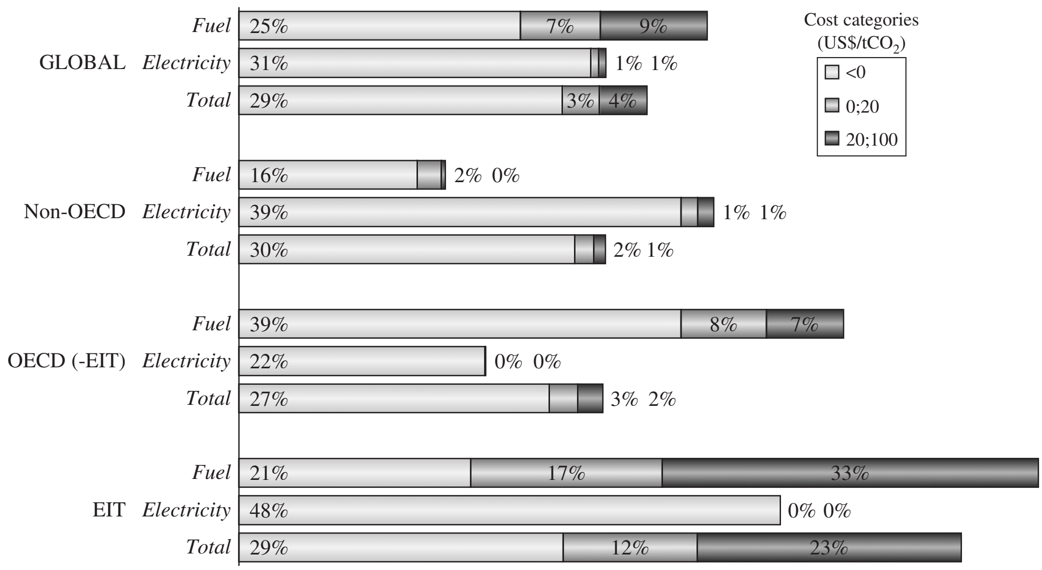


Fig. 2. Estimated potential for GHG mitigation at a sectoral level in 2030 in different cost categories. *For the buildings, forestry, waste and transport sectors, the potential is split into three cost categories: at net negative costs, at 0–20 US$/t$CO_2$, and 20–100 US$/tCO_2. For the industrial, forestry, and energy suppy sectors, the potential is split into two categories: at costs below 20 US$/t$CO_2$ and at 20–100 US$/t$CO_2$. *Source*: constructed based on IPCC (2007).

to the year 2030, the absolute figures of the building-related potential are the highest among the sectors considered in an assessment of the Fourth IPCC Assessment Report (IPCC, 2007), and therefore are significant as illustrated by Fig. 2. Due to the limited number of demand-side end-use efficiency options considered by the studies, the omission of non-technological options, the often significant co-benefits, as well as the exclusion of advanced integrated highly efficient buildings, the real potential is likely to be higher. The results of the calculations by region, by fuel/electricity source, and by cost category are presented in Fig. 3.

Our estimates show that the largest economic potential (at net negative costs) to mitigate CO_2 emissions in absolute and relative terms is concentrated in developing countries. If CO_2 reductions as the percentage of these emissions' baseline are considered, economies in transition are ranked second, while this position is occupied by developed countries for the absolute amounts of potential. For economies in transition and developed countries located in the North, the largest CO_2 mitigation potential results from fuel savings associated with heat-oriented measures. Conversely, in developing countries located in the South, electricity savings constitute the largest potential available if more efficient appliances and lights are used. This distribution of the potential also explains the difference in mitigation costs between developing and developed countries. The switch to more efficient appliances quickly pays back, while building shell retrofits and fuel switching, which can deliver approximately half of the potential in developed countries, are often more expensive.

After the discussion of the magnitude of the potential for CO_2 mitigation, the question arises: how much does it contribute to stabilisation of the global climate if realised? To answer this question, the IPCC SRES B2 scenario to



	Baseline Billion tons CO_2	Absolute values of potential in cost categories, Billion tons CO_2 (in US$/t$CO_2$)			
		<0	0–20	20–100	Total <100
Global	11.1	3.2	0.35	0.45	4.0
Non-OECD	5.0	1.5	0.10	0.05	1.6
OECD (-IET)	4.8	1.3	0.10	0.10	1.6
EIT	1.3	0.40	0.15	0.30	0.85

Fig. 3. Potential for CO_2 mitigation in buildings related to electric and fuel end-uses split into cost categories, 2020 (presented as shares of respective fuel- and electricity-associated baseline CO_2 emissions).

2030 is compared to what would happen if the potential estimates are extrapolated to 2030 by applying the above-described cost-effective mitigation options to buildings until this year. The SRES B2 has approximately 30% higher emissions in 2030 than in 2004 (11.4 vs. 8.6 Gt/year). If the cost-effective potential, estimated as approximately 30% of business-as-usual emissions, is realised, it would cancel the emission growth over 2004–2030 as projected by the B2 scenario. This level (if achieved by all other sectors) is consistent with Stabilisation Scenarios at 500–550 ppm CO_2eq. as presented by the Summary of Policymakers (IPCC, 2007), which would result in avoiding a 3°C temperature increase over the considered period of time.

7. Conclusion

This paper investigated the potential for CO_2 emission mitigation and associated costs in the world's buildings. The main conclusion is that substantial low cost reductions can be achieved over the coming years in energy-related CO_2 emissions in the buildings sector. If this potential is realised, the building-related CO_2 emissions would stay constant over 2004–2030. These stabilisation levels (if achieved by all other sectors) would cancel about 3°C temperature increase.

For the countries reviewed, developing countries can mitigate between 13% and 52% of the CO_2 emissions in 2020 cost effectively; for the industrialised countries this range is between 12% and 25%, whereas for economies in transition it is between 13% and 37%. Globally, at least 29% of the projected baseline emissions by 2020 can be avoided cost effectively through mitigation measures in the buildings sector. This represents the highest share of cost-effective opportunities among sectors. Additionally, at least 3% of baseline emissions can be avoided at costs up to 20 US$/t$CO_2$, and 4% more if costs up to 100 US$/t$CO_2$ are considered, although these latter figures are significantly underestimated due to the lack of proper assessment in the high-cost categories. These figures represent a global emission reduction of approximately 3.2, 3.6, and 4.0 billion tons of CO_2eq. in 2020, at 0, 20 US$/t$CO_2$, and 100 US$/tCO_2, respectively, assuming the baseline developed on the basis of the reviewed studies. Developing countries still have a higher abundance of "low-hanging fruits", while developed countries have already been capturing low-cost opportunities due to progressive policies in place or in the pipeline, but still have major remaining potentials to capture, and new opportunities continuously open. Switching to energy-efficient lighting was found to be the most attractive measure worldwide, in terms of both cost effectiveness and the size of the mitigation potential. The analysis shows that the highest potential in developing countries is associated with electricity savings from appliances and lights, while the highest potential in developed countries and economies in transition results from fuel savings. Generally, the potential associated with electricity savings is characterised by lower mitigation costs than fuel-associated savings.

The authors would like to highlight that the research results present a low estimate of the real potential. This is because of a critical lack of robust, comprehensive, detailed and up-to-date bottom-up assessments of GHG reduction opportunities and associated costs in buildings worldwide and especially in developing countries and economies in transition, and, even if such studies exist, they are often poorly documented and are not updated as time goes by. Also, the methodologies applied by such studies vary study by study; therefore, application of a harmonised methodology to mitigation research for different countries is a very challenging task, although a very important one from the global research and policy-making perspectives.

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Appendix A. A database of country-level CO_2 mitigation studies (those studies listed in the list of references are not repeated)

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Appendix B

See Table B1.

Table B1
Carbon dioxide emissions reduction potential for residential and commercial sectors

Country/ region	Reference	Type of potential	Description of mitigation scenarios	Potential		Measures with lowest costs	Measures with highest potential	Notes
				Million tCO_2	Baseline %			
Case studies providing information for demand-side measures								
EU-15	Joosen and Blok (2001)	Technical	25 options: retrofit (insulation); heating systems; new zero/low-energy buildings, lights, office equipment and appliances; solar and geo-thermal heat production; BEMS	310	21	1. Efficient TV and peripheries 2. Efficient refrigerators and freezers 3. Lighting best practice	1. Retrofit: insulated windows; 2. retrofit: wall insulation; 3. BEMS for space heating and cooling	[1].4%; [4].Fref.; [5].TY 2010.
		Economic		175	12			
Canada	Jaccard and Associates (2002)	Market	Mainly fuel switch in water and space heating, hot water efficiency and the multi-residential retrofit program in households; landfill gas, building shell efficiency actions, and fuel switch in commerce	22	24	N.A. (not listed in the study)	1. Electricity demand reductions; 2. commercial landfill gas; 3. furnaces and shell improvements	[1].10%; [5].TY 2010.
Greece	Mirasgedis et al. (2004)	Technical	14 technological options: fuel switch, controls, insulation, lights, air conditioning, and others	13	54	1. Replacement of central boilers; 2. use of roof ventilators; 3. replacement of AC	1. Shell, esp. insulation; 2. lighting and water heating; 3. space heating systems	[1].6%; [4].Fref.; [5].TY 2010; [7].R only
		Economic		6	25			
UK	DEFRA (2006)	Technical	41 options: insulation; low-e double glazing windows; various appliances; heating controls; better IT equipment, more efficient motors, shift to CFLs, BEMS, etc.	46	24 (res. only)	1. Efficient fridge/freezers; 2. efficient chest freezers; 3. efficient dishwashers	1. Efficient gas boilers; 2. cavity insulation; 3. loft insulation	[1].7–5%:R/C; [4].BL: Johnston et al. (2005); [5].BY 2005
Australia	Australian Greenhouse Office (2005)	Market	Fridges and other appliances, air conditioners, water heating, swimming pool equipment, chillers, ballasts, standards, greenlight Australia plan, refrigerated cabinets, water dispensers, standby	18	15	1. Standby programs; 2. MEPS for appliances 1999; 3. TVs on-mode.	1. Packaged air conditioners; 2. ballast program in 2003; 3. fluorescent bulbs	[1].5%; [4].BL: scenario without measures; [5].BY 2005
China	ERI (2004)	Enhanced market	Key policies: energy conservation standards, heat price reform, standards and labelling for appliances, energy efficiency projects, etc.	422	23	N.a. (Not listed in the study)	N.A. (not listed in the study)	[1].N.A.
Estonia	ESE and SEITC (1999)	Market	4 insulation measures: 3d window glass, new insulation into houses, renovation of roofs, additional attic insulation	0.4	2.5% of nation. emis.	1. New insulation; 2. attic insulation; 3. 3d window glass	1. New insulation; 2. 3d window glass; 3. attic insulation	[1].6%; [5].BY 1995; TY 2025

New EU Member State[a]	Petersdroff et al. (2005)	Technical	Building envelope esp. insulation of walls, roofs, cellar/ground floor, windows with lower U-value, and renewal of energy supply.	62	–	1. Roof insulation; 2. wall insulation; 3. floor insulation	1. Window replacement; 2. wall insulation; 3. roof insulation	[1].6%; [4].Fr-ef; [5].BY 2006; TY 2015
Hungary	Szlavik et al. (1999)	Technical	25 technological options and measures: building envelope, space heating, hot water supply, ventilation, awareness, lighting, appliances	22	45	1. Individual metering of hot water; 2. water flow controllers; 3. retrofitted windows	1. Post insulation; 2. retrofit of windows; 3. replacement of windows	[1].3%; [5].TY 2030
		Economic		15	31			
Myanmar	ADB (1998)	Economic	5 options: shift to CFLs, switch to efficient biomass and LPG cook stoves, improved kerosene lamps, efficient air conditioners	3	N.A.	1. Biomass cook stoves, 2. kerosene lamps, 3. CFLs	1. Biomass cook stoves, 2. LPG cook stoves, 3. CFLs	[1].10%
India	Reddy and Balachandra (2005)	Market	Lighting: mixture of incandescents, fluorescent tubes and CFLs, exchange of traditional kerosene and wood stoves and water heaters for efficient equipment	17	33	1. Efficient packages of lighting; 2. kerosene stoves; 3. wood stoves	1. Wood stoves, 2. efficient packages of lighting; 3. kerosene stoves	[1].N.A.; [5].TY 2010; [7].R only
Republic of Korea	ADB (1998)	Economic	7 options: heating–condensing gas boilers, solar hot water systems, insulation standards; cooling-air conditioners; improved light shift to fluorescents and CFLs; efficient motors and inverters	20	17	1. Heating: gas boilers, solar hot water, insulation standards; 2. air conditioners; 3. inverters and motors	1. Improved lights; 2. motors and inverters; 3. gas boilers, solar hot water system, insulation standards	[1].8.5%; [5].BY1998.
Thailand	ADB (1998)	Technical	3 technological programs: lighting (shift to fluorescents), refrigerator (insulation and compressors), and air conditioning	15	31	1. Lighting, 2. efficient refrigerators, 3. air conditioning	1. Efficient air conditioning, 2. efficient refrigerators, 3. lighting	[1].10%; [5].BY 1997; [7].R only
		Economic		6.1	13			
Pakistan	ADB (1998)	Technical	Energy efficiency improvements of electric appliances and other end-use devices such as lights, fans, refrigerators, water heaters, and improvement of building design	7	18	1. Improved lights, 2. efficient ceiling fans, 3. more efficient refrigerators	1. Efficient ceiling fans, 2. improved lights, 3. improved building design	[1].8%; [5].BY 1998
		Economic		6	16			
Indonesia	AIM (2004)	Technical	9 main technological options: energy-efficient appliances such as refrigerator and air conditioners, lights (shift from incandescents to fluorescents), kerosene, electricity and gas water heater, kerosene and gas heater, wall and window insulation, and others	13.5	25	Efficient refrigerator, electricity and gas water heater, kerosene and gas heater, lights, air conditioners (not ranked)	1. Efficient refrigerators, 2. fluorescent lamps, 3. efficient electric water heater (ranking at negative marginal cost)	[1].5%; [2].integrated assessment; [4].Fref.; [7].R only
		Economic		10.2	19			

Table B1 (*continued*)

Country/region	Reference	Type of potential	Description of mitigation scenarios	Potential		Measures with lowest costs	Measures with highest potential	Notes
				Million tCO_2	Baseline %			
Argentina	AIM (2004)	Technical		3.8	22			
		Economic		3.3	19			
Brazil	AIM (2004)	Technical		5.4	41			
		Economic		4.8	36			
Ecuador	FEDEMA (1999)	Economic	6 main options: improvements of appliances, lighting systems, electricity end-uses, esp. in rural areas and in the services, solar water heating, public lighting	7	52	1. Lights; 2. electric appliances (esp. rural areas); 3. electricity end-use in services	1. Improved electricity end-uses in rural areas; 2. electric appliances (esp. in rural areas); 3. light systems	[1].10%; [5].TY 2030
Poland	Gaj and Sadowski (1997)	Technical	13 options: lights in streets, commerce and households, gas boiler controls, appliances, heat meters, thermal insulation for walls and roofs, window tightening and replacement, fuel switch from coal to gas, solar or biomass, DH boilers	43	26	1. Efficient street lighting; 2. improved controls of small gas boilers; 3. efficient lighting in commerce	1. Insulation of walls, 2. improvement of home appliances, 3. fuel switching from coal to gas, solar, and biomass	[1].N.A.; [4].BL: 3NC UNFCCC, 2001
		Economic		30	18			
Russia	Izrael et al. (1999)	Technical	Downsized thermal generators (boilers and heaters), thermal insulation (improved panels, doors, balconies, windows), heat and hot water meters and controls, hot water distribution devices, electric appliances	182	47	N.A. (not listed in the study)	N.A. (not listed in the study)	[1].N.A.; [4].BL: 3NC UNFCCC; CENEf 2004; and www.opec.ru/; [5].TY 2010
		Economic		52	13			
South Africa	De Villiers and Matibe (2000); De Villiers (2000)	Technical	21 options: light practices; new and retrofits HVAC; stoves; thermal envelope; fuel switch in heaters; standards and labelling; for hot water: heat pumps, better insulation, efficient use; solar heating	41	23	1. Energy star equipment; 2. lighting retrofit; 3. new lighting systems	1. Hybrid solar water heaters; 2. new building thermal design; 3. new HVAC systems	[1].6%; [4].Fref.; [5].BY 2001; TY 2030.
		Economic		37	20			
Croatia	1NC UNFCCC	Market	Electricity savings for not heating purposes (low-energy bulbs, more efficient appliances, improved motors), solar energy use increase, thermal insulation improvement	2	14	1. Bulbs and appliances; 2. solar energy use increase; 3. insulation improvement	1. Insulation improvement; 2. solar energy use increase; 3. bulbs and appliances	[1].N.A.
Studies providing the information about both supply and demand-side options not separating them								
Germany	Martinsen et al. (2002)	Technical	Two options: fuel switch from coal and oil to natural gas and biomass, and heat insulation	31	26	N.A. (not listed in the study)	1. Heat insulation; 2. fuel switch from coal and oil to gas and biomass	[1].N.a.; [5].BY 2002; [7].R only.
	Lechtenbohmer et al. (2005)	Economic	Improvement in space and water heating, appliances and	81	37	N.A. (not listed in the study)	R: 1. Insulation; 2. heating systems, fuel switch,	

New EU Member States[b]			lighting, cooling/freezing, air conditioning, cooking, motors, process heat, renewable energies, reduced emissions from electricity generation				DH&CHP; C: 1. energy efficiency, 2. renewables	[1].3–5%; [5].BY 2005; [7].C includes agriculture
USA	Koomey et al. (2001)	Market	Voluntary labelling, deployment programs, building codes, new efficiency standards, government procurement, implementation of tax credits, expansion of cost-shared federal R&D expenditures	898	37	N.A. (The study did not examine a GHG potential supply cost curve.)	1. Lighting; 2. space cooling; 3. space heating	[1].7%; [5].BY 1997
Japan	Murakami et al. (2006)	Technical	47 options: new and retrofit insulation, double glazing window, home appliances (water and space heating/cooling, lighting, cooking), PVs, solar heating, shift to energy-efficient living style, low carbon electricity generation	46	28	N.A. (not listed in the study)	1. Water heater; 2. space heater; 3. home appliances	[1]. N.A.; [7].R only

Notes specify those parameters which are different from those identified below (the number of a note is the number of the model parameter) except Note 1, for which the respective note gives specific values: (1) discount rate (DR) belongs to the interval [3%; 10%]. (2) Most models are bottom-up. (3) All models consider CO_2. If a study considered GHGs, CO_2 only was analysed; if the study assessed C, potential was converted into CO_2. (4) Baseline (BL) is Business-As-Usual Scenario (BAU) or similar. (Frozen efficiency scenario is abbreviated as Fref.) (5) Base year (BY) is 2000; target year (TY) is 2020. (6) Costs covered: cost of incremental reduction, abatement costs, costs of avoided or saved or mitigated CO_2, marginal costs. (7) Estimations are made for residential (R) and commercial (C) sectors in sum. (8) Provides other important notes.

[a]Hungary, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Poland, and the Czech Republic.

[b]Latvia, Lithuania, Estonia, Slovakia, Slovenia, Hungary, Malta, Cyprus, Poland, and the Czech Republic.

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