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SPECIAL FEATURE: ORIGINAL ARTICLE Socio-technological transitions

Low-carbon transitions in world regions: comparison of technological mitigation potential and costs in 2020 and 2030 through bottom-up analyses

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Abstract This study focuses on low-carbon transitions in the mid-term and analyzes mitigation potentials of greenhouse gas (GHG) emissions in 2020 and 2030 in a comparison based on bottom-up-type models. The study provides in-depth analyses of technological mitigation potentials and costs by sector and analyzes marginal abatement cost (MAC) curves from 0 to 200 US \$/tCO_2 eq in major countries. An advantage of this study is that the technological feasibility of reducing GHG emissions is identified explicitly through looking at distinct technological options. However, the results of MAC curves using the bottom-up approach vary widely according to region and model due to the various differing assumptions. Thus, this study focuses on some comparable variables in order to analyze the differences between MAC curves. For example, reduction ratios relative to 2005 in Annex I range from 9 % to 31 % and 17 % to 34 % at 50 US \$/tCO_2 eq in 2020 and 2030, respectively. In China and India, results of GHG emissions relative to 2005 vary very widely due to the difference in baseline emissions as well as the diffusion rate of mitigation technologies. Future portfolios of advanced technologies and energy resources, especially nuclear and renewable energies, are the most prominent reasons for the difference in MAC curves. Transitions toward a low-carbon society are not in line with current trends, and will require drastic GHG reductions, hence it is important to discuss how to overcome various existing barriers such as energy security constraints and technological restrictions.

Keywords Bottom-up analysis · Marginal abatement cost · Technological mitigation potential · Low-carbon transition · Model comparison

Introduction

International negotiations under the United Nation Framework Convention on Climate Change (UNFCCC) have focused on mid-term targets for reducing greenhouse gas (GHG) emissions in the context of long-term GHG emission projections and climate change stabilization. The Intergovernmental Panel on Climate Change (IPCC) reported in the Fourth Assessment Report (AR4) Working Group 3 (WG3) that global CO_2 emissions need to be reduced by 30–85 % relative to emissions in 2000 by the year 2050 and CO_2 emissions need to peak and decline before 2020, to achieve the stringent GHG stabilization scenarios such as categories I to II in Table SPM 5 of the IPCC AR4 (see pp 15 of the SPM in the IPCC AR4 WG3). Based on the IPCC AR4 findings, policy-makers at the 15th Conference of the Parties (COP15) to the UNFCCC in 2009 focused on achieving a 2 °C global temperature limit above pre-industrial levels in the Copenhagen Accord (UNFCCC 2010a). After this Accord, the UNFCCC received submissions of governmental climate pledges to cut and limit GHG emissions by 2020 on a national scale (UNFCCC 2010b). In response to this political attention, the United Nation Environment Programme (UNEP) (UNEP 2010; Rogelj et al. 2011) reviewed studies on GHG emission pathways consistent with a global temperature limit at 2 °C above pre-industrial levels, and discussed the

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emission gap between estimated global emissions in 2020 under pathways to achieve the 2 °C target and the summation of national GHG emissions reduction targets pledged by 85 countries under the Copenhagen Accord. This Emissions Gap Report pointed out that the Copenhagen Accord Pledges are not sufficient to limit global warming to 2 °C, which corresponds approximately to GHGs stabilization categories I scenarios in the IPCC AR4, even if countries implement their conditional pledges.

It is important to analyze the level of GHG emissions around 2020 and 2030 and discuss the mid-term transition pathways on not only a global scale but also a national scale, in the context of long-term (beyond 2050) scenarios toward climate change stabilization. Especially, the analyses of mitigation potentials and costs on a global scale, as well as on a national scale in the mid-term (up to 2030), have been motivating policy makers to discuss whether the levels of national pledges are sufficient. Therefore, this study focuses on analyses of technological mitigation potentials and costs in 2020 and 2030 and conducts a model comparison study based on multi-regional and multi-sectoral energy-engineering models. This paper consists of five sections: "Background and objectives of this comparison study" introduces previous modeling comparison studies and sets out the objectives of this comparison study, "Comparison design on mitigation potentials and costs" explains the design of this comparison study, "Results and discussion" discusses the results of the comparison study and examines the difference in technological mitigation potentials and costs by sector in major GHG emitting countries, and "Conclusions" concludes with insights from this comparison study.

Background and objectives of this comparison study

This model comparison study on GHG emissions reduction potentials using a bottom-up based analysis has been conducted since 2008. This modeling comparison focuses on an in-depth analysis of mitigation potentials and costs from the view point of the mid-term (up to 2030) in the context of long-term (beyond 2050) climate change stabilization scenarios, and compares the estimated results by energy-engineering bottom-up type models for multi-regions and multi-sectors. Comparison of marginal abatement costs (MAC) by different models in 2020 and 2030 in the major GHG emitting countries/regions was conducted, and the reasons for differences in MAC by region were carefully analyzed because mitigation potentials and costs vary widely depending on various assumptions and data settings. Unlike previous studies reported in the IPCC AR4 and other comparison studies or papers, the following four aspects are focused on in this study.

Mid-term transition scenarios toward climate change stabilization

Table SPM. 5 in the IPCC AR4 WG3 shows stabilization scenarios in six different categories, and the most stringent stabilization level, i.e., Category I, which corresponds to an approximately 2 °C global temperature limit above pre-industrial levels, has attracted the attention of policy makers as a climate stabilization target. In addition, Box 13.7 in the IPCC AR4 WG3 (see pp 776 in the IPCC AR4 WG3), which gives information about mitigation targets in 2020 and in 2050 for Annex I Parties in the Kyoto Protocol for achieving global GHG stabilization targets of 450, 550 and 650 CO_2 eq ppm concentrations, indicates that GHG emissions in 2020 need to be reduced by between 25 and 40 % compared to the 1990 level of emissions in Annex I parties in order to achieve the 450 CO_2 eq ppm concentrations target. These findings in the IPCC AR4 WG3 have received a lot of attention in recent years during the international negotiation process. However, the background information of Table SPM. 5 (Hanaoka et al. 2006) and original literature of Box 13.7 (Den Elzen and Meinshausen 2006) did not provide detailed information on the feasibility of achieving such GHG mitigation targets and their mitigation costs in the mid-term (around 2020–2030). Since the IPCC AR4 was published, several modeling comparison studies have been done or are ongoing, such as the Energy Modeling Forum (EMF) 22 (Clarke et al. 2009), Adaptation and Mitigation Strategies (ADAM) (Edenhofer et al. 2010), Asia Modeling Exercise (AME), EMF 24 and so on. However, these modeling comparison studies focused mainly on long-term (up to 2100) climate stabilization scenarios. In light of that, this comparison study focuses on an in-depth analysis of the mid-term (2020–2030) transition scenarios analyzed using a global multi-region and multi-sector model.

Mitigation potentials in major GHG emitting countries by multi-regional analysis

The IPCC AR4 WG3 also pointed out that mitigation efforts over the next two to three decades will have a large impact on opportunities to achieve lower stabilization levels and that energy efficiency plays a key role in many scenarios for most regions and timescales (see pp 15–16 of the SPM in the IPCC AR4 WG3). Improved energy efficiency is one of society's most important instruments for combating climate change in the short- to mid-term. In order to reinforce these key messages, the role of energy intensity improvement in the GHG stabilization scenarios for six different categories on Table SPM. 5 in the IPCC AR4 WG3 were analyzed in detail for the short- to mid-term by Hanaoka et al. (2009). However, most of results were aggregated on a global scale due to a lack of data availability on a national scale and only one analysis has been done on multi-regional scales in Category IV on Table SPM. 5. Box 13.7 in the IPCC AR4 WG3, while its original literature (Den Elzen and Meinshausen 2006) also gives information on emission levels in Annex I groups in 2020 but does not indicate any key messages on a national scale. Therefore, this comparison study focuses on more detailed regional aggregations that cover the major GHG emitting countries and regions such as USA, EU27, Russia, China, India, Japan, the whole of Asia and Annex I, by using a global model with multi-regions.

Mitigation potentials and costs based on a multi-sectoral bottom-up analysis

Ecofys carried out a comparison study between bottom-up and top-down approaches to derive improved insights into mitigation potentials and to clarify the gap between the two different assessment approaches (Hoogwijk et al. 2008). The IPCC AR4 reviewed this study and reported mitigation potentials and costs for 2030 from both bottom-up and top-down studies in Figure SPM. 5, Table SPM. 1 and Table SPM. 2 (see pp 9–10 of the SPM in the IPCC AR4 WG3). However, the comparison results of the Ecofys report were compared on a global level, not on a regional level, and the bottom-up analysis was conducted using only one bottom-up methodology, while the top-down analyses were compared among several different models such as the computable general equilibrium model, energy system model and input–output model. In addition, the bottom-up approach used in the Ecofys report was based on an accounting methodology that compared baselines aggregated from different literature sources inconsistent among different sectors. This approach covered only technological GHG mitigation potentials associated with energy use but did not include non-CO_2 emissions in non-energy sectors (Hoogwijk et al. 2010). Therefore, it is necessary to compare the results of bottom-up analyses using not only one approach but several models that cover the basket of six GHGs in the Kyoto Protocol, because results from the bottom-up approach will vary widely depending on various assumptions such as socio-economic driving forces and technology information. In recent years, several international modeling comparison studies, such as EMF21 (Weyant et al. 2006), IMCP (Grubb et al. 2006), EMF22 (Clarke et al. 2009), ADAM (Edenhofer et al. 2010), have been carried out. These comparison studies focused on the long-term emission pathways (up to 2100) for GHG stabilization and its economic impacts by using mainly top-down models. However, it is also important to focus on comparison results of the technological feasibility of mitigation potentials and costs in the short- to mid-term (up to 2030), which is an area of specialty for the energy-engineering bottom-up type models, in order to achieve a stringent climate change stabilization target. Hence, this comparison study focuses mainly on technological mitigation potentials and their feasibility based on the multi-sectoral bottom-up model.

Comparison of the marginal abatement cost curve and its differences

The IPCC AR4 WG3 provides an analysis of mitigation options, GHG reduction potentials and costs by reviewing a variety of literature. For example, Tables 11.3 and 11.4 in Chap. 11 (see pp 632–634 in the IPCC AR4 WG3) show the range of mitigation potentials for different carbon prices from 0 to 100 US \$/tCO_2 eq in each sector in 2030. However, these mitigation potentials and costs vary widely depending on different models and the different settings for socio-economic assumptions, service demand assumptions, scope of mitigation options, and so on. The IPCC AR4 WG3 did not adequately describe the reasons for these wide ranges of mitigation potentials and costs due to space constraints. With regard to the range of carbon prices, Table 11.3 in the IPCC AR4 focuses on carbon prices under 100 US \$/tCO_2 eq, which is within the scope of the current trend of the carbon market. For example, the European Unit of Accounting (EUA) price of the European Union Emissions Trading Scheme (EU-ETS) and the Certified Emission Reduction (CER) price for Clean Development Mechanism (CDM) projects vary around 15–30 €/tCO_2 eq and 10–20 €/tCO_2 eq, respectively, and the value of penalty charges in the EU-ETS market is at 100 €/tCO_2 eq. However, transitions toward a low-carbon society are not an extension of the current trends and much greater GHG reductions than the current rate are required in the mid-term on a global scale (Rogelj et al. 2011; IEA 2010). It is also worth analyzing mitigation potentials at carbon prices higher than 100 US \$/tCO_2 eq. Therefore, this comparison study focuses on technological mitigation potentials up to the carbon price at 200 US \$/tCO_2 eq, which is close to double the price of penalty charges at 100 €/tCO_2 eq in the EU-ETS market. Moreover, Tables 11.3 and 11.4 in the IPCC AR4 show mitigation potentials only on a global scale and not on a detailed regional scale. Accordingly, this comparison study focuses on results of MAC curves from 0 to 200 US \$/tCO_2 eq in a more detailed country or region than the IPCC AR4 WG3, and provides comprehensive analysis to show the wide range of comparison results.

Comparison design on mitigation potentials and costs

Characteristics of the bottom-up approach

This comparison study focuses on the results of mitigation potentials and costs using energy-engineering bottom-up models for multi-regions and multi-sectors. The most characteristic aspect of the bottom-up approach is that it deals with distinct and detailed technology information such as the costs of technologies, energy efficiency of technologies, the diffusion rate of technologies, at regional and sectoral levels. The bottom-up analysis has two different approaches: an accounting approach that accumulates mitigation options compared to the baseline scenario, and a cost optimization approach that minimizes the total system costs. One of the advantages of the bottom-up approach is that the technological feasibility of GHG emission reductions is identified explicitly by mitigation options. However, in the bottom-up analysis it is difficult to take into account the spillover effects of the introduction of mitigation measures (Edenhofer et al. 2006), such as changes in industrial structure, service demand, technology costs and energy prices. Consequently, it is not possible to analyze its economic impacts (Akashi and Hanaoka 2012; Wagner et al. 2012; Akimoto et al. 2012). On the other hand, the top-down approach focuses on economies and systems as a whole, and analyzes economic impacts by considering various economic parameters such as price elasticity and changes in economic structures. However, it cannot deal explicitly with mitigation measures. In recent years, another method called "Hybrid" modeling (Hourcade et al. 2006) has been discussed to reconcile bottom-up and top-down approaches in order to analyze both technological aspects and its economic impacts. A hybrid model is an ideal model, but there have still been systematic challenges and there are not yet many hybrid models on a global scale with multi-regions and multi-sectors. In general, the top-down approach produces a larger estimated amount of mitigation potentials than the bottom-up approach (IPCC 2007; Hoogwijk et al. 2010), because the bottom-up approach is based on technological information under the limitations of data availability, for example, a lack of data availability of innovative technologies, a lack of coverage of mitigation technologies in certain sectors and so on.

Another important feature of the bottom-up approach is that it is suitable for the analysis of the technological feasibility in the short to mid-term (for example, Hanaoka et al. 2009b; Akimoto et al. 2010), but it is difficult to apply this approach to the long-term (beyond 2050) analysis because there is the limitations of data availability to set distinct and detailed data of mitigation technologies in multi-sectors and multi-regions for the long-term future, whereas the top-down approach (e.g., van Vuuren et al. 2011; Thomson et al. 2011; Masui et al. 2011) examines the long-term analysis by assuming economic parameters based on data from historical trends or future outlooks.

Both the bottom-up and top-down approach have merits and demerits, but this comparison study focuses more on the technological feasibility of mitigation potentials and costs in 2020 and 2030, based on the results from the bottom-up analysis, in order to assess the transitions in major GHG emitting countries, especially in Asian regions.

Overview of comparison design

This comparison study focuses on MAC curves estimated by using energy-engineering bottom-up type models. In order to analyze the reasons for the difference in MAC curves by region, several major variables are focused on to compare different models. In addition, to analyze mid-term GHG emissions mitigation targets in 2020 and 2030, major GHG emitting countries and regions as well as the global scale are compared. Table 1 shows the comparable variables and geographical breakdowns, and Table 2 an overview of participating models in this comparison study. When developing models in general, approaches adopted for regional aggregations in world regions differ depending on the purpose of the analysis. It is important to note the caveat that some models do not accurately fit into the regional classification such as Annex I or OECD shown in Table 1. In such a case, the original regional classifications of each model are aggregated approximately in order to fit more closely to the regional definition of Annex I or OECD in Table 1. All models include six GHGs regulated under the

Table 1 Comparable variables used in this study

	Items
Socio-economic information	Population, GPD
Emissions	Baseline emissions
Mitigation potentials from baseline	Mitigation potentials by sector under several carbon prices
Energy consumptions	Primary energy consumptions by energy type
Major mitigation options	Carbon capture and storage
Global and major groups	Global, OECD, Non-OECD, Annex I, Non-Annex I, Asia
Major countries and regions	USA, EU27, Russia, China, India, Japan

Table 2 Overview of models participating

Model	Model type	Regions	Gases	Sectors	Organization	Reference
AIM/Enduse	Bottom-up model	Global 32 regions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6	Multi-sectors excluding LULUCF	NIES, Japan	Akashi and Hanaoka (2012)
DNE21+	Bottom-up model	Global 54 regions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6	Multi-sectors excluding LULUCF	RITE, Japan	Akimoto et al. (2012)
GAINS	Bottom-up model	Annex I 40 regions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6	Multi-sectors excluding LULUCF	IIASA, Austria	Wagner et al. (2012)
GCAM	Hybrid model including bottom-up	Global 14 regions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6	Multi-sectors including LULUCF	PNNL, US	Thomson et al. (2011)
McKinsey	Bottom-up cost curves	Global 21 regions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6	Multi-sectors including LULUCF	McKinsey International	McKinsey and Company (2009a, b)

Kyoto Protocol and cover multi-sectors. However, the coverage of mitigation measures differs from one to another. For example, GCAM and McKinsey include mitigation potentials considering carbon sinks in the Land Use, Land Use Change and Forestry (LULUCF) sector in the UNFCCC classification; however, AIM/Enduse[Global], DNE21+, and GAINS exclude mitigation potentials in LULUCF. In addition, resolutions of sectors and definitions of service demands in these sectors differ from one to another in some sectors. For example, DNE21+ and McKinsey divide the industry sector into steel, cement, paper and pulp, chemicals, and others, but AIM/Enduse defines steel, cement, and others and GCAM defines cement and others based on the different purposes of development of each model.

Harmonizing the baseline is an important issue but a complicated discussion on which to reach a consensus across the different models in Table 2, because model structures differ from each other, such as the difference of regional aggregations in the world regions, difference of sectoral resolutions, difference of units of various service demands and so on. Moreover, in a bottom-up type analysis, there are several ways to set a baseline scenario by explicitly describing technology features such as a fixed-technology scenario, a business-as-usual (BaU) scenario considering autonomous energy efficiency improvement. This study compares mitigation potentials and costs without harmonizing the baseline and focuses on the technological feasibility of mitigation potentials in multi-sectors and multi-regions in the mid-term in more detail than the previous comparison studies. The methodology of how to compare different models and its results are described in the next chapter.

Results and discussion

Comparison of marginal abatement cost curves

According to the IPCC AR4 (IPCC 2007), mitigation potentials are defined as “the scale of GHG reductions that could be achieved, relative to emission baselines, for a given carbon price (expressed in cost per unit of carbon dioxide equivalent emissions avoided or reduced)”. Thus, MAC is defined as the abatement costs of a unit reduction of GHG emissions relative to emission baselines. This comparison study follows the same definition and MAC curves in 2020 and 2030 in major GHG emitting countries are shown in Fig. 1 by plotting mitigation potentials relative to the baseline for the each model at a certain carbon price. These MAC curves imply technological mitigation potentials and technological implementation costs resulting from the bottom-up approach, which considers various factors such as the current level of energy efficiencies, difference of socio-economic characteristics by country, and scope of renewable energies.

However, even at the same carbon price in the same country, mitigation potentials vary widely according to the model, especially for higher carbon pricing both in developed and developing countries. The differences in MAC curve features are caused by various factors in the bottom-up analyses; for example (1) the settings of socio-economic data and other driving forces; (2) the settings of key advanced technologies and their future portfolios; (3) the assumptions of energy resource restrictions and their portfolios, and future energy prices; (4) model components such as the coverage of target sectors, target GHGs, and mitigation options; (5) coverage of costs, such as initial cost, operation and management costs, transaction costs, and related terms, such as the settings of the discount rate and payback period; (6) base year emissions; and (7) the assumptions of baseline emissions. It is important to focus on all these differences when comparing the robustness of MAC curves, but it is difficult to compare all the factors because a MAC curve is a complicated index based on complex modeling results. Consequently, this comparison study focuses on some of these factors in order to analyze the differences in MAC curves.

In the IPCC AR4 (IPCC 2007), a baseline is defined as “the reference from which an alternative outcome can be

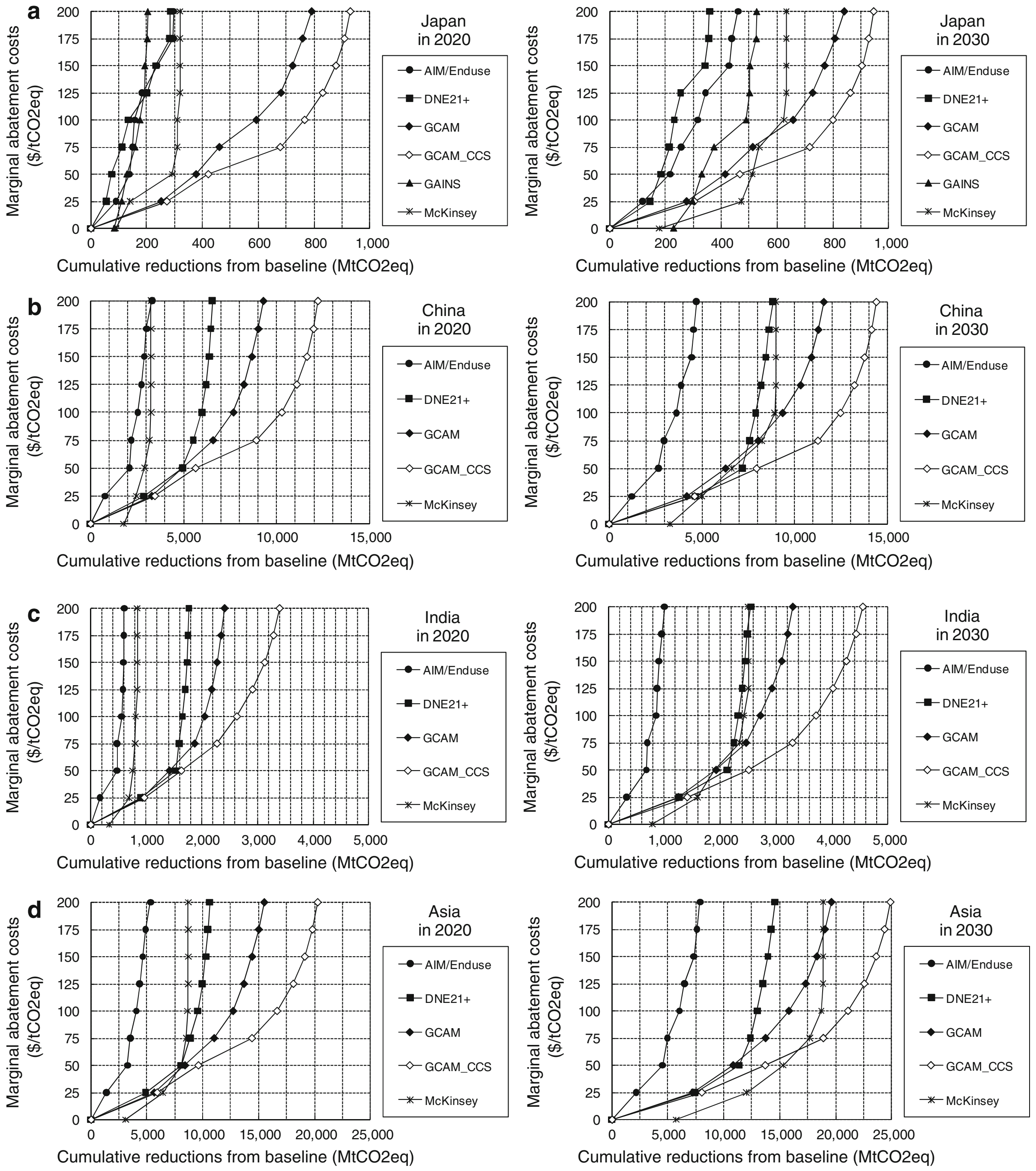


Fig. 1 Comparison of marginal abatement cost (MAC) curves in 2020 and 2030 in major greenhouse gas (GHG)-emitting countries and regions. **a** Japan in 2020 and 2030. **b** China in 2020 and 2030. **c** India in 2020 and 2030. **d** Asia in 2020 and 2030. **e** US in 2020 and 2030. **f** EU27 in 2020 and 2030. **g** Russia in 2020 and 2030. **h** Annex I in 2020 and 2030. **i** Non Annex I in 2020 and 2030

measured, for example, a non-intervention scenario is used as a reference when analyzing intervention scenarios". However, there are various ways of setting a baseline (i.e., a non-intervention) scenario, such as a business as usual (BaU) scenario, and a fixed-technology scenario. A fixed technology scenario is sometimes used in a bottom-up analysis based on the concept that the future energy share and energy efficiency of the standard technologies in each sector are fixed at the same levels as those for the base year (for example, see Table 6.2 on pp 412 and Box 6.1 on pp 413 in the IPCC AR4 WG3). By considering the currently observed trends, a BaU scenario is generally set based on the assumption that autonomous energy efficiency improvements in standard technologies will occur.

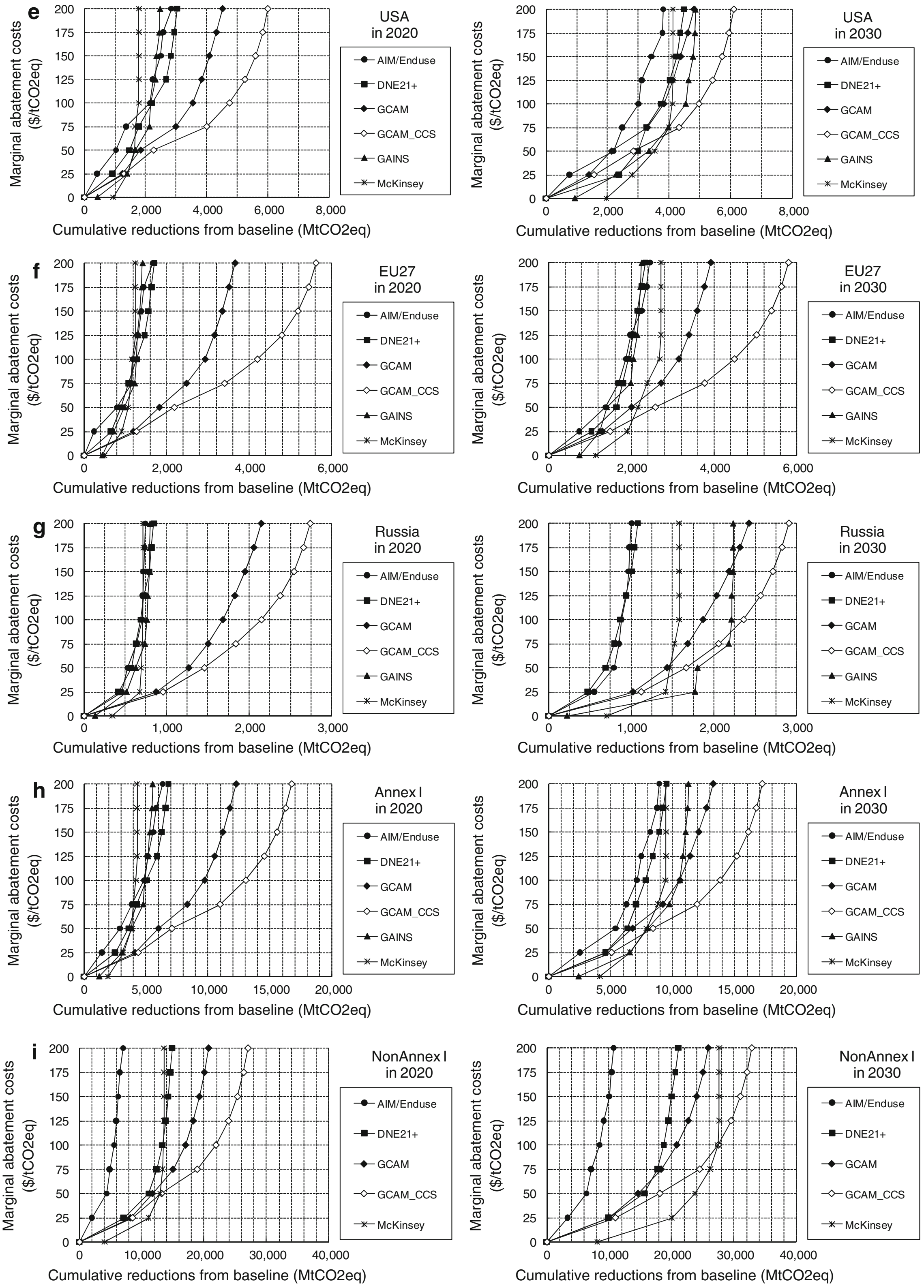


Fig. 1 continued

Comparison of the methodology on how to set a BaU scenario is a considerable proviso but outside the scope of this study because BaU scenarios fluctuate due to various factors. The settings of a baseline scenario influence the amount of mitigation potentials and subsequently the features of MAC curves.

In Fig. 1, if a baseline scenario considers autonomous energy efficiency improvements in technologies as a BaU (e.g., GAINS and McKinsey), sometimes the MAC can show a negative net value (so called "no-regret") because a given technology may yield enough energy cost savings to more than offset the costs of adopting and using the baseline technology. However, even if it is no-regret, these mitigation options cannot be introduced without imposing initial costs and introducing policy pushes because they occur due to various existing barriers such as market failure and lack of information on efficient technologies. Thus, it is important to eliminate such social barriers to diffuse these efficient technologies. On the other hand, if a baseline scenario is set under the cost-optimization assumptions and considers mitigation measures of autonomous energy efficiency improvements as well as measures under negative net values (e.g., AIM/Enduse[Global], DNE21+, GCAM), mitigation potentials are cumulated only by mitigation options with positive carbon prices. The difference in assumptions for the baseline scenario causes the different amount of mitigation potentials at the 0 \$/tCO_2 case. By imposing a carbon price, the higher the carbon price becomes, the wider the range of mitigation potentials. Reasons for this are discussed in the following sections.

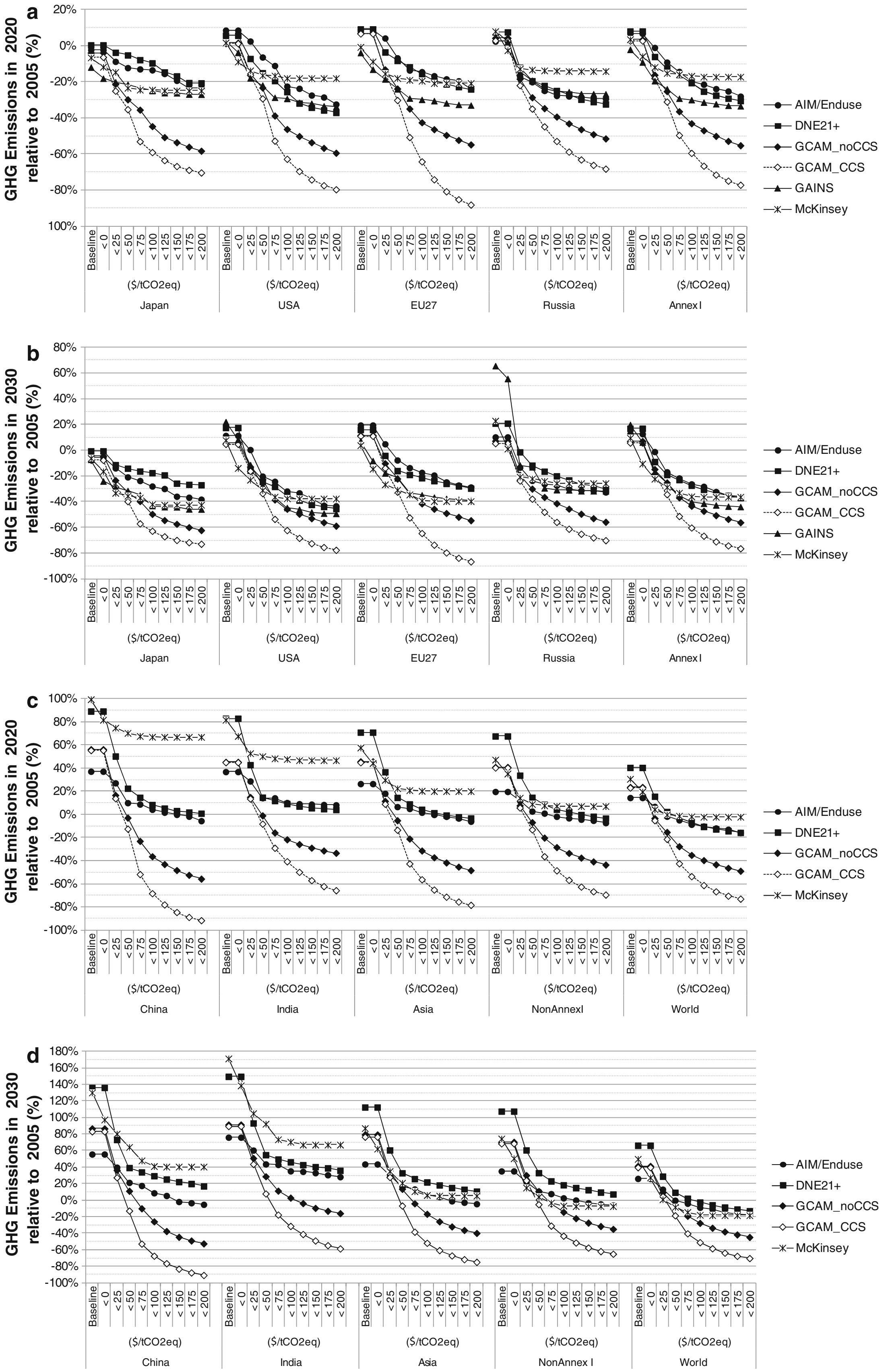
Marginal abatement costs and reduction ratio relative to the 2005 level

Figure 1 shows the wide range of MAC results in all regions but, as mentioned previously, the amount of cumulative reductions and resulting emission levels at a certain carbon pricing are different depending on how the baseline scenario is set. Accordingly, in order to compare the amount of GHG emissions, Fig. 2 shows the ratio of GHG emissions at a certain carbon price as well as the baseline emissions in 2020 and 2030 relative to the 2005 level for the major GHG emitting Annex I and non Annex I countries. Figure 2a, b indicate that results of the baseline emissions vary more in non-Annex I countries than in Annex I countries.

Even though the features of MAC curves in Fig. 1 are similar from one model to the other in a certain country (for example MAC curves in Russia in 2020 and 2030 by AIM/Enduse and DNE21+ in Fig. 1g), when the level of mitigation potentials are converted to the level of GHG emissions at a certain carbon price, the level of GHG emissions relative to the 2005 level shows different results due to the different assumptions made for the baseline emission projections (Fig. 2a, b). According to the results, the higher the carbon price becomes, the greater the range of the reduction ratio relative to 2005 is. In Annex I countries, the reduction ratio relative to 2005 becomes larger and the range of its reduction ratio becomes wider at a carbon price above 50 US\$/tCO_2 eq due to the effects of a drastic energy shift and the different portfolios of advanced mitigation measures. For example, the ranges of the reduction ratio relative to 2005 in Annex I are from 9 to 31, 17 to 60 and 17 to 77 % at 50, 100 and 200 US\$/tCO_2 eq, respectively, in 2020, and from 17 to 34, 26 to 60 and 36 to 76 % at 50, 100 and 200 US\$/tCO_2 eq, respectively, in 2030. In non-Annex I countries, especially China and India, results of GHG emissions relative to 2005 vary widely not only for the baseline scenario but also for the policy intervention scenario under different carbon pricing. Factors relating to the difference in amount of mitigation potentials will be discussed in the following sections, so reasons for difference in the level of baseline GHG emission are evaluated in this section. Figure 3a shows the scatter plot for annual GDP growth rate and annual population growth rate in different regions from the time horizon of 2005 to 2030, and Fig. 3b shows annual growth rate of GHG emissions in the baseline in different regions in different models from the same time horizon of 2005 to 2030. As is shown in Fig. 3b, the range of annual GHG emission changes is much larger in China and India than those in developed countries.

Fig. 2 GHG emissions in 2020 and 2030 relative to the 2005 level ▶ under a certain carbon price in major GHG-emitting countries. **a** Annex I countries in 2020. **b** Annex I countries in 2030. **c** Non Annex I countries and the world in 2020. **d** Non Annex I countries and the world in 2030

GDP and population are the main key drivers for estimating GHG emissions in the baseline case, and diversity of annual growth rates can be seen more in GDP than in population in China, India and Russia in Fig. 3a. Population prospects were almost the same among different models (Fig. 3a). Therefore, it can be considered that the higher the annual growth rate of GDP, the wider the annual growth rates of GHG emissions observed in the baseline (Fig. 3b). It is also indispensable to compare other driving forces derived from GDP changes such as steel production and cement production in the industry sector, transport volumes in the transport sector, energy consumption in the building sector. This study attempts to compare these service demands for multi-sectors and multi-regions, but sectoral resolutions and definition of drivers differ from one model to another. Although it is interesting to discuss the wide diversity of future service demands and social structural changes from the viewpoint of transitions in


a
GHG Emissions in 2020 relative to 2005 (%)
20%
0%
-20%
-40%
-60%
-80%
100%
b
GHG Emissions in 2030 relative to 2005 (%)
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
c
GHG Emissions in 2020 relative to 2005 (%)
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
d
GHG Emissions in 2030 relative to 2005 (%)
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
Baseline
< 0
< 25
< 50
< 75
< 100
< 125
< 150
< 175
< 200
($/tCO2eq)
Japan
USA
EU27
Russia
Annex I
China
India
Asia
NonAnnexI
World
AIM/Enduse
DNE21+
GCAM_noCCS
GCAM_CCS
GAINS
McKinsey

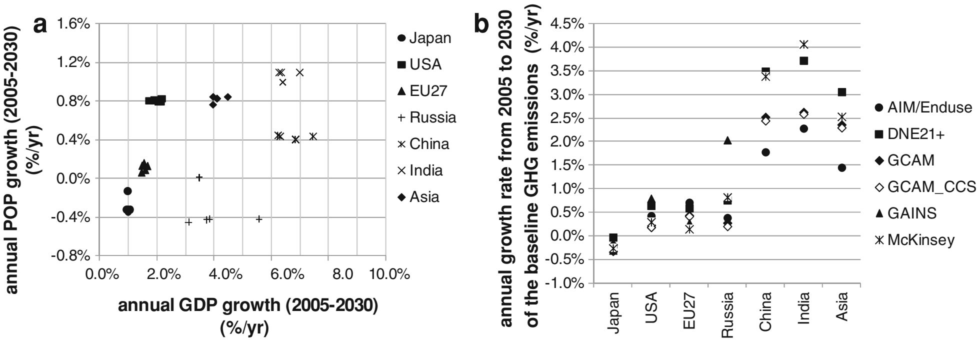


Fig. 3 Scatter plot of **a** GDP growth versus population growth and **b** difference in GHG emissions change in the baseline, for the time horizon 2005–2030

developing Asian countries, it is outside of the scope of this study to compare detailed driving forces due to the limitations of comparable variables.

Technological mitigation potentials and costs by sector and by region

In Figs. 1 and 2, differences in MAC curves and GHG emissions ratios relative to 2005 are examined, showing a wide range of results. Mitigation potentials by region and by sector at a certain carbon price are summarized in Tables 3 and 4, and the results of this study are compared with the results shown in Tables 11.3 and 11.4 in Chap. 11 of the IPCC AR4 (IPCC 2007). It is important to note that, when comparing mitigation potentials by sector, definition of mitigation potentials (i.e., direct emission or indirect emission) need to be clarified carefully. In Table 11.3 in the IPCC AR4, mitigation potentials in the building and industry sectors are divided into electricity savings and fuel savings, and potential in the power generation sector shows all options excluding electricity savings in other sectors in order to avoid double counting of mitigation potentials. That is to say, Table 11.3 in the IPCC AR4 shows mitigation potential in indirect emissions in which CO_2 emissions from the power sector are allocated to each sector in proportion to the amount of electricity consumption of each sector. However, in this comparison study, mitigation potentials by sector are compared in the definition of direct emissions. Accordingly, the information in Table 11.3 in the IPCC AR4 is converted to direct emissions (i.e., the amount of electricity savings are counted in the power generation sector) and compared with this study. It should also be noted that Table 11.3 in the IPCC AR4 shows cost categories of 0, 20, 50, and 100 \$/tCO_2 eq and Table 11.4 in the IPCC AR4 shows a cost category under 27.3 \$/tCO_2 eq, which are different cost ranges from Tables 3 and 4 in this study. Therefore, the results in the IPCC AR4 fit approximately into similar cost ranges[1] as in Tables 3 and 4 in this study.

As is shown in Tables 3 and 4, large reduction potentials can be seen in the power and industry sectors compared to other sectors, and a wide range of reduction potentials are observed, with mitigation options in these sectors having a large effect on different features in MAC curves. In order to discuss the results of differences in MAC curves, it is necessary to focus on energy-related CO_2 emissions, especially energy compositions and mitigation measures resulting from the industry and power sectors. In the transport and agriculture sectors, reduction potentials in the world shown in the IPCC AR4 are within the range of this comparison study, and the number of digits of high reduction potentials in this study is quite similar to the results in the IPCC AR4. The differences between this comparison study and that of the IPCC AR4 in the transport and agriculture sectors may result from differences in the assumptions regarding baseline emissions, coverage of mitigation options and diffusion of these mitigation options.

Decomposition analyses: explanation of the range of mitigation potentials

Although the power generation and industry sectors are found to be the major sectors influencing differences in MAC curves, it is not clear why MAC curves are so different. It is important to discuss changes in service demands and diffusion of efficient technologies on the demand side, but due to a difficulty of data availability of comparing such detailed data for multi-regions and multi-sectors, this is not assessed here. Instead, in order to assess the differences in MAC curves, the Kaya identity (Yamaji et al. 1991) is modified to address the impact of CCS technology and the effects of fuel switching from high-carbon fossil fuels to less carbon-intensive fossil or non-carbon energies such as nuclear and renewable energies in primary energy supply, as follows:

$$\mathrm{CO_2} = \frac{\mathrm{CO_2}}{\mathrm{CO_2e}} \cdot \frac{\mathrm{CO_2e}}{\mathrm{TPES}} \cdot \frac{\mathrm{TPES}}{\mathrm{GDP}} \cdot \mathrm{GDP} \qquad (1)$$

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[1] Mitigation potentials under 20 US \$/tCO_2 eq in Table 11.3 and 27.3 US \$/tCO_2 eq in Table 11.4 in the IPCC AR4 are fitted to mitigation potentials under 25 US \$/tCO_2 eq in Tables 3 and 4 in this study.

Table 3 Technological greenhouse gas (GHG) mitigation potentials from baseline in 2020

Sector	Country	Technological mitigation potentials from baseline in 2020 (MtCO$_2$)						
		<0 US\$/tCO$_2$ Low–high	<25 US\$/tCO$_2$ Low–high	<50 US\$/tCO$_2$ Low–high	<75 US\$/tCO$_2$ Low–high	<100 US\$/tCO$_2$ Low–high	<150 US\$/tCO$_2$ Low–high	<200 US\$/tCO$_2$ Low–high
All	Japan	0–90	56–272	75–421	111–679	135–766	194–879	205–930
	China	0–1,774	777–3,451	2,103–5,632	2,198–8,890	2,547–10,262	2,888–11,611	3,259–12,196
	India	0–336	171–962	477–1,629	478–2,268	564–2,626	593—3,128	606–3,393
	Asia	0–3,099	1,377–6,456	3,265–9,600	3,531–14,391	4,068–16,641	4,649–19,121	5,344–20,275
	US	0–954	420–1,401	1,035–2,260	1,361–3,994	1,783–4,737	1,787–5,585	1,787–5,987
	EU27	0–502	245–1,270	801–2,187	1,077–3,403	1,166–4,200	1,249–5,182	1,249–5,618
	Russia	0–343	416–955	528–1,456	629–1,835	688–2,146	720–2,540	720–2,736
	Annex I	0–1,948	1,426–4,352	2,903–7,071	3,846–10,949	4,191–13,028	4,289–15,544	4,289–16,723
	Non Annex I	0–4,073	2,026–11,139	4,416–13,150	4,872–18,860	5,583–21,861	6,243–25,318	7,017–27,000
	World	0–6,020	3,452–14,317	7,319–20,221	8,737–29,809	10,464–34,889	11,905–40,862	13,673–43,722
	World (IPCC TAR)		13,200–18,500					
Power	Japan	0–0	5–77	9–97	27–274	43–324	125–389	164–414
	China	0–0	133–1,816	860–3,671	1,231–3,988	1,384–4,354	1,664–5,413	1,967–5,941
	India	0–0	36–478	278–1,034	269–1,193	334–1,429	348–1,806	351–2,003
	Asia	0–0	294–2,734	1,713–5,506	1,885–5,895	2,149–7,283	2,608–9,192	3,135–10,123
	US	0–0	58–388	406–913	689–2,325	1,402–2,850	1,684–3,525	1,912–3,828
	EU27	0–0	147–297	412–710	516–1,553	662–2,118	849–2,896	883–3,218
	Russia	0–0	73–283	76–506	172–681	210–850	218–1,085	235–1,199
	Annex I	0–0	424–1,114	1,300–2,351	2,183–5,188	2,884–6,584	3,634–8,461	3,872–9,285
	Non Annex I	0–0	347–3,359	1,992–6,674	2,272–7,323	2,667–8,645	3,140–11,222	3,700–12,511
	World	0–0	771–4,473	3,292–8,566	4,455–12,022	5,725–15,229	6,773–19,683	7,946–21,797
	World (IPCC TAR)		1,300–2,600					
Industry	Japan	0–0	1–163	2–226	3–258	4–279	5–313	7–326
	China	0–0	55–2,071	151–3,144	151–4,005	299–4,435	288–4,641	345–4,664
	India	0–0	16–231	26–349	29–449	35–488	40–514	44–524
	Asia	0–0	104–2,863	232–4,315	239–5,466	428–6,036	435–6,366	518–6,442
	US	0–0	14–253	17–385	18–490	24–556	52–614	69–638
	EU27	0–0	0–403	4–615	0–792	0–887	0–962	0–986
	Russia	0–0	9–246	12–367	12–456	24–517	26–580	26–604
	Annex I	0–0	13–1,141	31–1,708	0–2,144	0–2,406	32–2,655	67–2,748
	Non Annex I	0–0	115–3,309	255–5,051	278–6,457	476–7,156	496–7,608	601–7,752
	World	0–0	129–4,450	285–6,760	246–8,600	462–9,562	527–10,262	668–10,500
	World (IPCC TAR)		5,170–5,870					

Table 3 continued

Sector	Country	Technological mitigation potentials from baseline in 2020 (MtCO_2)						
		$<0\ \text{US\$/tCO}_2$ Low–high	$<25\ \text{US\$/tCO}_2$ Low–high	$<50\ \text{US\$/tCO}_2$ Low–high	$<75\ \text{US\$/tCO}_2$ Low–high	$<100\ \text{US\$/tCO}_2$ Low–high	$<150\ \text{US\$/tCO}_2$ Low–high	$<200\ \text{US\$/tCO}_2$ Low–high
Transport	Japan	0–0	0–24	0–39	0–52	0–63	0–78	0–89
	China	0–0	0–113	0–187	0–246	0–296	0–372	0–427
	India	0–0	0–29	0–48	0–64	0–78	0–99	0–115
	Asia	0–0	0–269	0–446	0–591	0–715	0–906	0–1,046
	US	0–0	0–196	0–326	0–437	0–517	0–662	0–774
	EU27	0–0	0–136	0–224	0–297	0–354	0–448	0–519
	Russia	0–0	0–36	0–61	0–81	0–96	0–123	0–143
	Annex I	0–0	0–421	0–699	0–931	0–1,108	0–1,410	0–1,641
	Non Annex I	0–0	0–409	0–679	0–896	0–1,087	0–1,381	0–1,600
	World	0–0	0–830	0–1,378	0–1,824	0–2,195	0–2,792	0–3,241
	World (IPCC TAR)		1,100–2,600					
Buildings	Japan	0–0	0–26	0–45	0–61	0–73	0–91	0–103
	China	0–0	0–318	0–480	0–585	0–655	0–725	13–762
	India	0–0	30–68	38–85	51–114	53–134	75–154	75–166
	Asia	0–0	68–433	78–673	79–847	85–969	90–1,102	99–1,181
	US	0–0	2–60	4–116	9–170	12–222	17–299	24–349
	EU27	0–0	3–106	3–185	3–256	0–320	0–411	2–471
	Russia	0–0	0–74	1–125	1–169	1–207	2–266	2–308
	Annex I	0–0	6–276	8–495	13–689	14–863	18–1,122	30–1,294
	Non Annex I	0–0	77–511	88–799	88–1,014	98–1,171	101–1,348	112–1,455
	World	0–0	82–788	96–1,294	102–1,703	111–2,034	119–2,469	142–2,749
	World (IPCC TAR)		3,700–4,000					
Agriculture	Japan	0–1	2–9	3–9	4–9	4–9	3–9	3–9
	China	0–76	87–240	102–274	131–294	138–308	140–327	141–341
	India	0–48	78–226	105–296	113–345	132–385	145–448	145–490
	Asia	0–603	271–1,361	332–1,361	377–1,361	412–1,428	439–1,444	444–1,444
	US	0–39	78–191	125–216	129–230	135–240	135–254	135–264
	EU27	0–25	47–227	59–227	68–255	73–279	94–315	96–342
	Russia	0–39	18–151	21–151	23–151	27–153	31–153	34–153
	Annex I	0–124	274–582	300–701	322–772	337–826	379–906	392–965
	Non Annex I	0–703	363–2,226	432–2,280	483–2,377	524–2,504	561–2,683	573–2,803
	World	0–827	637–2,737	732–2,902	805–3,148	861–3,329	940–3,588	964–3,766
	World (IPCC TAR)		1,300–2,800					

Table 3 continued

Sector	Country	Technological mitigation potentials from baseline in 2020 ($MtCO_2$)						
		<0 US\$/tCO_2 Low–high	<25 US\$/tCO_2 Low–high	<50 US\$/tCO_2 Low–high	<75 US\$/tCO_2 Low–high	<100 US\$/tCO_2 Low–high	<150 US\$/tCO_2 Low–high	<200 US\$/tCO_2 Low–high
Waste	Japan	0–6	0–9	0–10	0–10	0–10	0–10	0–10
	China	0–19	0–130	0–130	0–163	0–195	0–260	0–260
	India	0–11	0–23	0–23	0–23	0–29	0–35	0–40
	Asia	0–157	0–225	0–227	0–271	0–324	0–422	0–446
	US	0–93	0–135	0–135	0–135	0–190	0–219	0–248
	EU27	0–24	0–60	0–74	0–87	0–99	0–110	0–121
	Russia	0–31	0–33	0–37	0–54	0–63	0–71	0–71
	Annex I	0–165	0–267	0–342	0–406	0–505	0–580	0–624
	Non Annex I	0–430	0–490	0–490	0–556	0–647	0–821	0–856
	World	0–594	0–758	0–794	0–962	0–1,152	0–1,401	0–1,480
	World (IPCC TAR)		730–730					

The range of cumulative mitigation potentials under a certain carbon price are shown

$$= \frac{CO_2}{CO_2e} \cdot \frac{CO_2e}{\sum_j PE_j} \cdot \frac{\sum_j PE_j}{TPES} \cdot \frac{TPES}{GDP} \cdot GDP \qquad (2)$$

$$\equiv sc \times co \times sf \times ei \times g$$

where, CO_2 is net CO_2 emissions; CO_2e is CO_2 emissions from fossil fuels and industry excluding carbon sinks; PE is primary energy supply; j is fossil fuel type (i.e., oil, gas, coal); TPES is total primary energy supply including fossil fuels, nuclear and renewables; GDP is economic activity; sc is share of net CO_2 to CO_2 emissions excluding carbon sinks; co is emissions coefficient; sf is share of fossil fuels in the total primary energy supply; and ei is energy intensity.

By using the four factors in Eq. (2), the following features can be analyzed for differences in MAC curves.

sc	The effects of carbon absorption measures (i.e., the ratio of net CO_2 emissions to CO_2 emissions from fossil fuels and industry excluding carbon sinks).
co	CO_2 emissions coefficient from fossil fuels (i.e., the ratio of CO_2 emissions to the primary energy supply from fossil fuels).
sf	The effects of fuel switching on the primary energy supply (i.e., the ratio of fossil fuel consumption to the total primary energy supply).
ei	The energy intensity (i.e., the amount of total primary energy supply per economic activity).

Figure 4 shows the example results of decomposition analyses in Japan, China, India, the US and EU27 in 2030, by using the extended Kaya identity described above. Figure 4a indicates the comparison of "sc" under a certain carbon price with "sc" under the baseline and reflects the effects of changes in the ratio of carbon absorption measures. The more CCS is introduced in the power and industry sectors, the lower "sc" becomes (less than 100 % relative to the baseline). With regard to carbon absorption measures, GCAM consider both CCS in the power and industry sectors and carbon sinks in the LULUCF sector; however, AIM/Enduse[Global], DNE21+ consider only CCS. It is found in Fig. 4a by comparing GCAM_CCS and GCAM_noCCS that the effects of carbon sinks in the LULUCF sector are estimated to be small. Therefore, it is more important to focus on the effects of CCS. The number of "sc" by AIM/Enduse and DNE21+ becomes lower than the baseline as the carbon price rises due to the effects of CCS in 2030 to some extent; however, GCAM_CCS estimates a large amount of CCS compared to other models. For example, the GCAM_CCS scenario shows negative emissions due to the effects of introducing biomass power plants with CCS in India in 2030. The amount of CCS is one of the reasons for the large difference in MAC results.

Table 4 Technological GHG mitigation potentials from baseline in 2030

Sector	Country	Technological mitigation potentials from baseline in 2030 ($MtCO_2$)						
		<0 US$/$tCO_2$ Low–high	<25 US$/$tCO_2$ Low–High	<50 US$/$tCO_2$ Low–high	<75 US$/$tCO_2$ Low–high	<100 US$/$tCO_2$ Low–high	<150 US$/$tCO_2$ Low–high	<200 US$/$tCO_2$ Low–high
All	Japan	0–229	119–472	184–511	214–718	231–801	342–905	358–948
	China	0–3,280	1,232–4,995	2,659–7,957	2,950–11,273	3,635–12,488	4,451–13,789	4,713–14,425
	India	0–785	329–1,593	683–2,505	696–3,286	859–3,708	906–4,249	1,008–4,543
	Asia	0–5,737	2,181–12,032	4,535–15,306	4,968–18,913	6,046–21,127	7,332–23,647	7,896–24,921
	US	0–1,962	762–2,794	2,124–3,520	2,479–4,320	3,006–4,965	3,425–5,720	3,804–6,101
	EU27	0–1,140	742–1,898	1,380–2,573	1,682–3,765	1,869–4,484	2,150–5,380	2,250–5,791
	Russia	0–705	474–1,775	694–1,806	793–2,183	869–2,359	970–2,713	1,004–2,907
	Annex I	0–4,137	2,537–6,566	5,399–8,405	6,275–11,966	7,119–13,838	8,204–16,105	8,910–17,224
	Non Annex I	0–8,077	3,364–20,039	6,395–23,742	7,145–26,184	8,472–27,483	10,016–31,010	10,713–32,844
	World	0–12,214	5,901–26,605	11,927–31,642	13,596–36,441	15,814–41,322	18,492–47,115	20,064–50,068
	World (IPCC AR4)	6,100	13,500	19,500		24,000		
Power	Japan	0–0	58–92	99–148	133–312	134–360	205–422	204–439
	China	0–0	171–3,381	1,245–5,672	1,470–5,808	1,790–5,977	2,535–6,465	2,717–6,999
	India	0–0	180–723	411–1,476	409–1,925	537–2,224	561–2,650	622–2,873
	Asia	0–0	556–4,829	2,234–8,327	2,522–8,906	3,094–9,930	4,196–11,909	4,592–12,879
	US	0–0	213–1,805	791–2,332	1,509–2,553	1,966–3,013	2,214–3,629	2,371–3,909
	EU27	0–0	366–678	608–1,132	1,059–1,879	1,272–2,404	1,383–3,127	1,461–3,422
	Russia	0–0	22–293	153–528	174–728	187–906	247–1,118	255–1,219
	Annex I	0–0	1,155–3,131	2,018–4,573	3,639–5,869	4,396–7,158	4,944–8,885	5,341–9,633
	Non Annex I	0–0	864–5,432	2,828–10,300	3,390–11,747	4,156–12,222	5,373–14,581	5,827–15,896
	World	0–0	2,019–8,563	5,762–14,873	7,155–16,750	8,690–19,067	10,710–23,465	11,780–25,528
	World (IPCC AR4)		5,440	7,030		7,870		
Industry	Japan	0–0	1–154	2–214	17–245	21–265	26–294	28–305
	China	0–0	160–2,536	202–4,016	206–4,991	507–5,370	489–5,559	494–5,612
	India	0–0	13–362	31–591	34–738	43–783	54–812	87–826
	Asia	0–0	186–3,634	274–5,723	309–7,085	699–7,624	722–7,950	776–8,083
	US	0–0	0–274	4–421	5–526	26–581	36–624	50–649
	EU27	0–0	0–402	0–635	0–806	0–883	0–942	0–967
	Russia	0–0	8–251	25–385	51–476	54–528	70–580	78–602
	Annex I	0–0	0–1,158	0–1,773	14–2,201	0–2,423	134–2,622	116–2,711
	Non Annex I	0–0	194–4,277	281–6,834	301–8,530	719–9,211	803–9,667	900–9,881
	World	0–0	93–5,435	217–8,607	315–10,731	709–11,634	937–12,289	1,016–12,592
	World (IPCC AR4)		880	3,080		3,230		

Table 4 continued

Sector	Country	Technological mitigation potentials from baseline in 2030 ($\mathrm{MtCO_2}$)						
		<0 $\mathrm{US\$/tCO_2}$ Low–high	<25 $\mathrm{US\$/tCO_2}$ Low–High	<50 $\mathrm{US\$/tCO_2}$ Low–high	<75 $\mathrm{US\$/tCO_2}$ Low–high	<100 $\mathrm{US\$/tCO_2}$ Low–high	<150 $\mathrm{US\$/tCO_2}$ Low–high	<200 $\mathrm{US\$/tCO_2}$ Low–high
Transport	Japan	0–0	0–32	0–51	0–64	0–75	0–91	0–104
	China	0–0	0–184	0–319	0–345	0–398	0–486	0–559
	India	0–0	0–56	0–87	0–108	0–116	0–144	0–168
	Asia	0–0	0–447	0–690	0–848	0–971	0–1,191	0–1,376
	US	0–0	0–286	0–446	0–562	0–620	0–769	0–893
	EU27	0–0	0–195	0–302	0–378	0–424	0–521	0–602
	Russia	0–0	0–60	0–93	0–116	0–130	0–161	0–187
	Annex I	0–0	0–616	0–959	0–1,202	0–1,344	0–1,660	0–1,922
	Non Annex I	0–0	0–668	0–1,030	0–1,271	0–1,446	0–1,779	0–2,059
	World	0–0	0–1,285	0–1,989	0–2,473	0–2,789	0–3,438	0–3,981
	World (IPCC AR4)	350	1,750	1,900		2,050		
Buildings	Japan	0–0	0–28	0–47	1–62	0–74	0–90	0–103
	China	0–0	2–343	0–523	0–633	0–701	0–770	0–811
	India	0–0	23–74	23–121	26–159	26–181	26–205	26–221
	Asia	0–0	36–499	21–781	0–976	0–1,101	0–1,240	42–1,333
	US	0–0	1–65	17–124	28–180	35–230	43–303	48–353
	EU27	0–0	2–113	2–196	3–269	4–329	3–416	8–477
	Russia	0–0	0–74	0–126	0–170	0–207	1–264	8–305
	Annex I	0–0	2–294	21–518	32–716	41–883	56–1,128	74–1,301
	Non Annex I	0–0	46–611	27–960	0–1,208	0–1,372	0–1,559	40–1,687
	World	0–0	48–905	47–1,478	26–1,924	29–2,255	54–2,687	114–2,988
	World (IPCC AR4)	1,700	2,100			2,610		
Agriculture	Japan	0–1	4–10	5–10	6–10	7–10	8–11	9–13
	China	0–66	150–328	176–328	224–328	238–409	242–409	243–409
	India	0–44	140–247	186–336	193–397	193–450	209–527	209–577
	Asia	0–608	479–1,959	584–1,959	660–1,959	720–2,062	767–2,079	775–2,079
	US	0–48	44–237	98–242	129–245	154–249	195–263	211–273
	EU27	0–34	77–428	97–428	112–428	120–428	147–428	149–428
	Russia	0–46	31–256	36–256	39–256	44–258	47–258	49–258
	Annex I	0–162	445–897	486–897	522–900	541–913	594–937	604–1,019
	Non Annex I	0–742	638–3,487	756–3,593	843–3,600	913–3,700	977–3,717	997–3,717
	World	0–904	1,083–4,385	1,241–4,490	1,365–4,499	1,454–4,614	1,570–4,630	1,601–4,630
	World (IPCC AR4)		1,600	2,700		4,400		

Table 4 continued

Sector	Country	Technological mitigation potentials from baseline in 2030 ($MtCO_2$)						
		<0 US\$/tCO_2 Low–high	<25 US\$/tCO_2 Low–High	<50 US\$/tCO_2 Low–high	<75 US\$/tCO_2 Low–high	<100 US\$/tCO_2 Low–high	<150 US\$/tCO_2 Low–high	<200 US\$/tCO_2 Low–high
Waste	Japan	0–13	0–20	0–20	0–20	0–20	0–20	0–20
	China	0–32	0–250	0–250	0–313	0–335	0–418	0–418
	India	0–20	0–50	0–50	0–50	0–62	0–67	0–79
	Asia	0–365	0–446	0–449	0–534	0–591	0–710	0–739
	US	0–233	0–261	0–261	0–261	0–261	0–261	0–261
	EU27	0–69	0–104	0–104	0–108	0–124	0–139	0–153
	Russia	0–58	0–64	0–64	0–74	0–74	0–74	0–74
	Annex I	0–416	0–504	0–504	0–562	0–631	0–656	0–670
	Non Annex I	0–1,000	0–1,133	0–1,133	0–1,133	0–1,169	0–1,372	0–1,402
	World	0–1,417	0–1,637	0–1,637	0–1,637	0–1,799	0–2,028	0–2,072
	World (IPCC AR4)	400	580	680		720		

The range of cumulative mitigation potentials under a certain carbon price are shown

Figure 4b indicates the comparison of “co” under a certain carbon price with “co” under the baseline and reflects the effects of changes in the CO_2 emissions coefficient resulting from a shift from high-carbon fossil fuels to less carbon-intensive fossil fuels and improvements in the energy industry. The more the shift to low-carbon fuels takes place, the lower “co” becomes (i.e., less than 100 % relative to the baseline). In Fig. 4b, the effect of the energy shift from high-carbon fossil fuels to less carbon-intensive fossil fuels can be seen in Japan, the US and EU27 among all models, but the degree of its shift is different from one study to another. For example, in the US, scenarios by DNE21+ and GCAM_noCCS estimate more energy shifts from coal power generations to gas power generations, whereas the scenario by AIM/Enduse and the GCAM_CCS retain coal power generations with CCS, so the number of “co” relative to the baseline is lower than those in DNE21+ and GCAM_noCCS. In India and China by AIM/Enduse and in Russia by both GCAM_CCS and GCAM_noCCS, “co” shows an increase relative to the baseline. This indicates that, even though CO_2 emissions are reduced by imposing carbon prices, the effects of CO_2 reductions are caused by shifting to the coal power plant with CCS and the ratio of CO_2 emissions to the primary energy supply from fossil fuels does not decrease relative to the baseline.

Figure 4c indicates the comparison of “sf” under a certain carbon price with “sf” under the baseline and reflects the effects of changes resulting from a shift from carbon-intensive fossil fuels to non-carbon energies (non-fossil fuels), such as nuclear and renewable energies. The more the shift to non-carbon energies takes place, the lower “sf” becomes (i.e., less than 100 % relative to the baseline). In Fig. 4c, the effect of fuel switching from carbon-intensive fossil fuels to non-carbon energies can be seen across all countries among all models. However, GCAM allows a drastic energy shift from fossil fuels to biomass in the GCAM_noCCS scenario and to nuclear and biomass in the GCAM_CCS scenario, compared to AIM/Enduse and DNE21+. Therefore, the effects of a drastic energy shift to non-carbon energies are another characteristic of large differences in MAC curves. With the technology selection framework under the least cost methodology, such a drastic energy shift may occur if it is cost effective. With regard to discussions on transitions in 2020 and 2030, it is also important to take into account political and social barriers such as energy security, energy costs and technological restrictions in different sectors and regions (as described in chapters of the IPCC AR4 WG3 report). It is widely accepted that achieving large GHG mitigation requires various mitigation measures regarding the use of less-carbon intensive fossil fuels, the shift to non-fossil fuel energies and promotion of advanced technologies, yet it

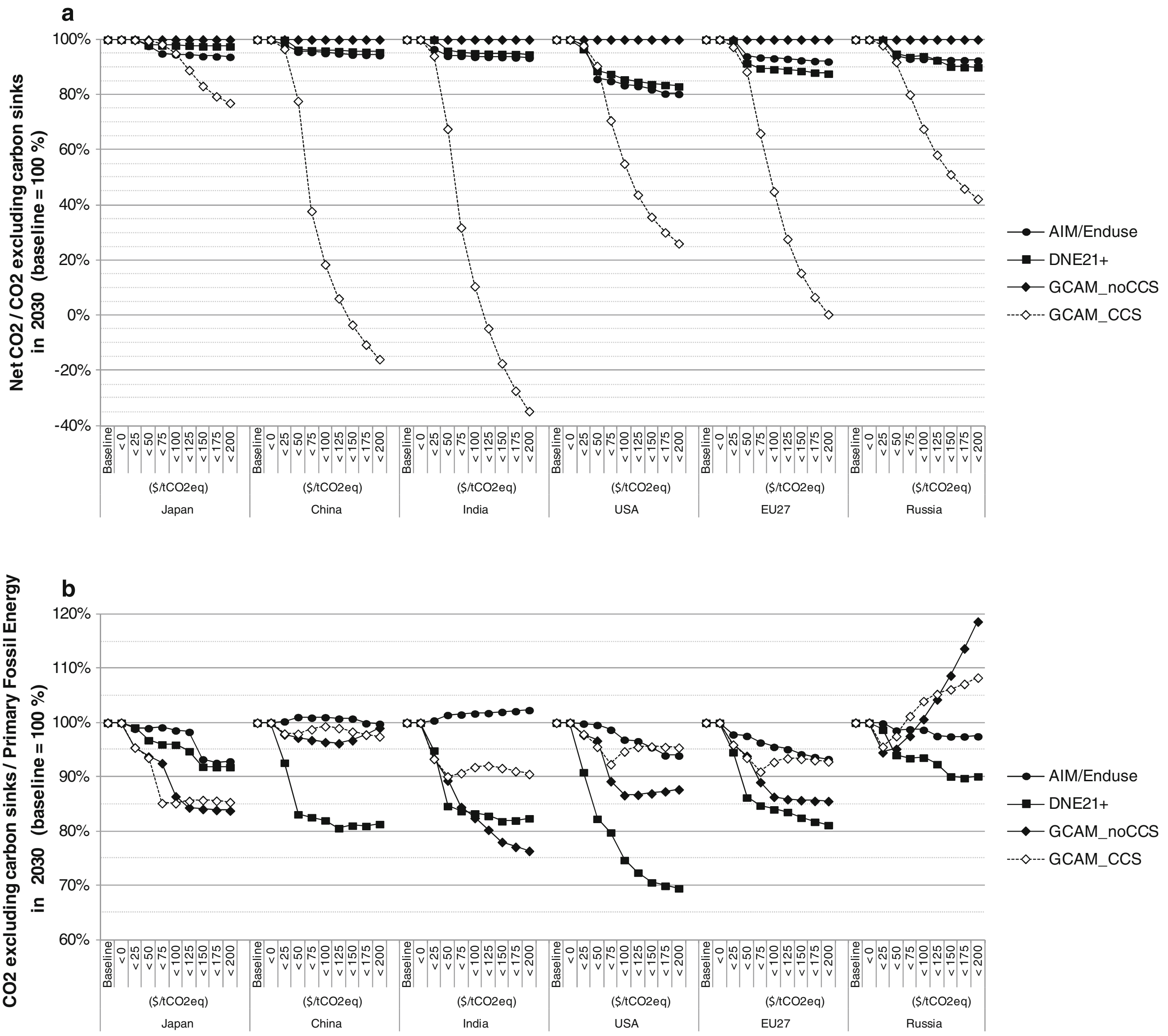

Fig. 4 Decomposition of CO_2 emissions in some key factors. **a** The effects of absorption measures. **b** The CO_2 emissions coefficient from fossil fuels. **c** The effects of fuel switching in primary energy supply. **d** The energy intensity

remains controversial to discuss the composition of power sources, based on assumptions of energy resource restrictions and their portfolios in each country (IEA 2010, 2011).

Figure 4d indicates the comparison of "ei" under a certain carbon price with "ei" under the baseline and describes the effects of changes resulting from energy efficiency improvements at the end-use points and energy-saving activities derived from changes in countries' social structure. In Fig. 4d, all models except for the GCAM_CCS scenario show the effects of energy efficiency improvements in all countries, but the speed of their improvement as the carbon price rises is different depending on the model. Only the GCAM_CCS scenario shows an increase in the total primary energy supply above costs of around 75 $/tCO_2$ because the GCAM_CCS scenario introduces a large amount of CCS as shown in Fig. 4a and it can allow increases in total energy consumption even though CO_2 emissions are decreased. An interesting point is that AIM/Enduse and DNE21+ do not take into account spillover effects of changes in the industrial structure and service demands, so Fig. 4d indicates the effects of energy efficiency improvements at the end-use points.

Implications and provisos of this comparison study

From the viewpoints of policy decision-making on GHG emissions reduction targets for each country in 2020 and 2030, equitable emission allocation has been one of foremost topics in the international framework. Policy-makers agreed on global average temperature increase below 2 °C and were interested in a much lower global temperature limit such as a

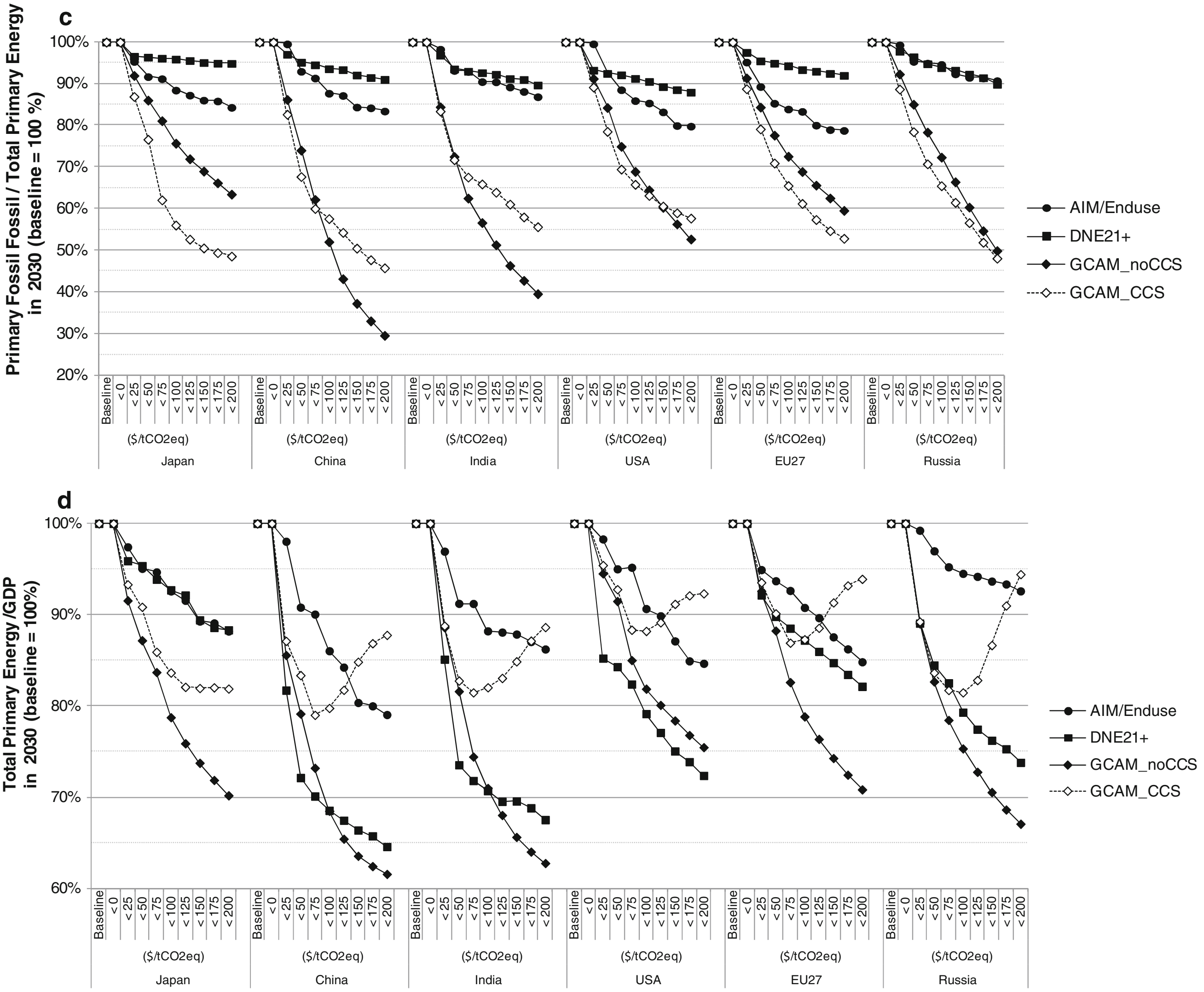

Fig. 4 continued

1.5° C target above pre-industrial levels by 2100. However, when it comes to the mid-term targets such as the year 2020 and 2030, decision making is also influenced by arguments and rights based on cumulative historical emissions among OECD and economies in transition (Hohne et al. 2011). A variety of criteria for equitable emission allocation has been proposed by various countries and experts. For example, Kanie et al. (2010) summarized the various previous studies in the large classification as:

1. "Responsibility" for emitting GHGs such as emission per capita, historical responsibility for temperature rise.
2. "Capacity" to pay for mitigation measures such as GDP, GDP per capita, human development index[2] (HDI).
3. "Capability" of potentials for mitigation measures such as emission per unit of production, emission per GDP, MAC.
4. Hybrid criteria considering several of these criteria.

The MAC discussed in this study gives useful information on the criterion of "capacity" of technological mitigation potentials for equitable emission allocation among countries. However, it is important to pay attention to some provisos relating to the limitations of the bottom-up analyses as described in "Comparison of marginal abatement cost curves".

Another important discussion on transitions toward a low-carbon society is that such a society is not in line with the current trends (Rogelj et al. 2011; United Nation Environment Programme 2010), and policy pushes and social behavior changes are thought to be required to achieve stringent GHG emissions reduction targets such as

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[2] A composite index measuring average achievement in three basic dimensions of human development—a long and healthy life, knowledge and a decent standard of living, defined by the United Nations Development Programme (UNDP).

a 2 °C target or a 50 % reduction target by 2050 compared to the 1990 level. In order to analyze such a stringent GHG emissions pathway, bottom-up analyses indicate mitigation options need to be selected under the framework of cost competitiveness. As a result, when a high carbon price is imposed, the result shows a drastic energy shift from coal or oil to gas, nuclear or renewable energies such as biomass and solar. These results imply that, if such an energy shift provides cost effectiveness at a certain carbon price, then the existing coal and oil power plants need to be retired even before their lifetime and be replaced by alternative low-carbon power plants. Such an analysis indicates a valuable implication for ideal decision-making on investments from the viewpoint of lowing GHG emissions in the whole country or world, because once a large plant with a long lifetime is built, then there is a lock-in effect (see, e.g., McKinsey and Company 2009a, b) and it is difficult to change social structures. Various social and political barriers such as energy security, resource constraints, technological restrictions, investment risks, and uncertainties on cost information including technology costs and transaction costs exist in the real world. The composition of fossil fuel energy types is not flexible depending on a country's situation, and energy shifts in 2020 and 2030 will be restricted to a certain amount (IEA 2010). As a result, how to discuss energy portfolios such as nuclear and renewable energies in each country, especially in 2020 and 2030, is a controversial topic among scientists as well as policy-makers, even though it is essential to discuss drastic mid-term transition pathways in the context of the long-term climate change stabilization.

With regard to discussions on cost analysis, assumptions on future energy prices and settings of a payback period and a discount rate also influence the results of mitigation potentials and costs. The way in which future energy prices are assumed will depend on how to analyze domestic and international energy markets and energy resources. It intricately influences the results; thus it is important but difficult to compare these effects among different models in this study, because energy prices are calculated endogenously in some models whereas they are assumed exogenously in other models. The setting of a discount rate and a payback period in a bottom-up approach is another key factor that has an impact on the results of technological mitigation costs. For example, if technological mitigation costs are accounted for over the full lifetime of each technology from the viewpoint of society-wide benefits (i.e., a payback period is considered over the full lifetime of the technology option), technological mitigation costs will become lower and the results of technology selections will be different, while technological mitigation potentials will become larger even at the same carbon price. However, a short payback period is obviously preferable to a long payback period especially for private investors (i.e., private industries and actors) because they assume a high risk for investing in energy conserving technologies. In other words, the payback period will be shorter than the full lifetime of each technology option. Even though it is essential to take note of it, it is difficult to compare the effects of these assumptions in this study, because the settings of the discount rate for investments and the payback period by sector and by country are different among different models.

Conclusions

By conducting the comparison study based on energy-engineering bottom-up models, technological mitigation potentials and costs in 2020 and 2030 were analyzed by sector in major countries, and the reasons for differences in MAC curves from 0 to 200 US $/tCO$_2$ were discussed. It can be concluded that:

1. MAC curves are influenced by various factors such as the settings of socio-economic data, the settings of diffusions of key advanced technologies, the assumptions of energy resource restrictions, the settings of technology costs and energy prices, and the assumption of the baseline emissions.
2. A large amount and a wide range of GHG reduction potentials are observed in the power and industry sectors compared to other sectors and, as a result, mitigation options in these sectors have an influence on different features of MAC curves. Especially, future technology portfolios of advanced technologies such as CCS and energy portfolios of nuclear and renewable energies, are the most prominent factors affecting the difference of MAC curves.
3. In Annex I countries for example, the ranges in the reduction ratio relative to 2005 are from 9 to 31 %, 17 to 60 % and 17 to 77 % at 50, 100 and 200 US$/tCO$_2$ eq, respectively, in 2020, and from 17 to 34 %, 26 to 60 % and 36 to 76 % at 50, 100 and 200 US$/tCO$_2$ eq, respectively, in 2030. The range of mitigation potentials becomes wider as the carbon price rises.
4. In non-Annex I countries, results of GHG emissions relative to 2005 vary very widely due to the difference of the baseline emissions being influenced by the wide range of driving forces as well as various other factors. This underlies the importance of discussing a wide diversity of driving forces, energy portfolios and technology portfolios especially in developing Asian countries.

This comparison study demonstrates the technological feasibility of mitigation potentials under cost-effective decision making. However, there are several provisos due to the limitations of the bottom-up analyses, and various social and political barriers that exist in the real world. Transitions toward a low-carbon society, which requires the achievement of stringent GHG emissions reduction targets such as a 2 °C target or a 50 % reduction target by 2050 compared to the 1990 level, are not an extension of the current trends. Accordingly, it is controversial but essential to discuss feasible energy portfolios and technology portfolios for 2020 and 2030 while considering the characteristics of each country, in order to provide robust MAC curves to policy makers.

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