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Co-benefit Reductions of Short-Lived Climate Pollutants and Air Pollutants by 2050 while Achieving the 2 Degree Target in Asia

***Tatsuya Hanaoka**[*1], **Toshihiko Masui**[2]*

[1]Center for Social and Environmental Systems, National Institute for Environmental Studies Institution, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan

e-mail: hanaoka@nies.go.jp

[2]Center for Social and Environmental Systems, National Institute for Environmental Studies Institution, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan

e-mail: masui@nies.go.jp

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ABSTRACT

This study analyses co-benefit reductions of short-lived climate pollutants and air pollutants due to the effects of carbon dioxide mitigation measures for achieving a 2 °C global temperature change limit above pre-industrial levels. This study focuses on the following points: an estimation of technological mitigation potentials and costs of the greenhouse gases (a), and an assessment of co-benefit mitigations of short-lived climate pollutants and air pollutants in Asia due to the effects of low-carbon measures (b). Mitigation measures such as energy efficiency improvement in the demand sectors and the shift to less-carbon intensive or non-fossil fuel energies in the supply sector play important roles in reducing carbon dioxide as well as short-lived climate pollutants and air pollutants largely, especially in rapidly developing countries in Asia. Emissions of methane, black carbon, sulphur dioxide, nitrogen oxide, and fine particulate matter in Asia are reduced around 23%, 63%, 73%, 27% and 65% in 2050 correspondingly, compared to the 2010 levels due to the co-benefits in drastic carbon dioxide mitigation measures. These co-benefits are much larger than effects of taking measures only for air pollutant reductions.

KEYWORDS

2 °C target, Low-carbon measures, Short-lived climate pollutants, Air pollutants, Co-benefits.

INTRODUCTION

The stringent Greenhouse Gases (GHGs) stabilization scenarios to achieve a 2 °C global temperature limit above pre-industrial levels, so called the “2 °C target”, were mentioned for the first time by the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) in 2007 [1]. Based on these scientific findings of the IPCC AR4, in the international negotiation process under the United Nation Framework Convention on Climate Change (UNFCCC), policy-makers at the 15th Conference of the Parties (COP15) to the UNFCCC in 2009 touched upon the

[*] Corresponding author

2 °C target in the Copenhagen Accord [2] and UNFCCC parties submitted their national GHG emissions reduction targets in 2020. However, it was pointed out that the emission gaps between the 2 °C target pathways and the global GHG emissions' trend considering the summation of these national reduction targets in 2020 pledged under the Copenhagen Accord would still largely remain [3]. Since the IPCC AR4, various papers have discussed how to achieve the 2 °C target and focused on analysing the role of negative CO_2 emissions for achieving low GHG emission pathways consistent with the 2 °C target, for example, analyses on ranges of global emissions pathways and temperature increases by the end of the century [4], comparisons of mitigation strategies among different Integrated Assessment Models focusing on the role of bio-energy in combination with carbon capture and storage [5], and evaluations of key technologies and its feasibility up to 2050 both in Asia and the world [6]. The IPCC fifth Assessment Report (AR5) in 2014 reviewed the cutting-edge scientific findings after the IPCC AR4, discussed both the feasibility and difficulties in achieving the 2 °C target, and summarized the emission gaps between the pledged GHG emissions under the Copenhagen Accord and the 2 °C target pathways or even more stringent ones like the 1.5 °C target [7]. After the IPCC AR5 was published, prior to the 21st Conference of the Parties (COP21) to the UNFCCC held in Paris in 2015 [8], 148 countries/regions in the world submitted their national GHG emissions reduction targets to the UNFCCC. These targets are called Intended Nationally Determined Contributions (INDCs) [9]. Thereafter, policy-makers from the UNFCCC participant countries at last agreed on decisions in COP21 that nations take efforts on climate mitigation actions for achieving the mid- to long-term GHG emissions pathways consistent with a global temperature change limit below 2 °C compared to the pre-industrial level [8]. However, it was once again pointed out by the UNEP report [10] and by estimation tools on the website [11], that the INDCs' GHG emissions under the Paris Agreement would not yet be enough to reach to the 2 °C target pathways.

In order to achieve the 2 °C target, the accelerated introduction of energy efficient technologies on both the demand side and the supply side all over the world, even in developing countries, is required. Energy efficiency improvement plays a key role not only at the beginning of the twenty-first century but also in the latter half of the century in most regions [1, 12]. However, the rate of change in energy intensity improvement on the global scale, including the effects of energy efficiency improvement, would be limited [12]. Thus, the timing of peaking-out of global emissions has an impact on the emissions pathways in the latter half of century, and it is necessary to fill the gap between the pledged GHG emissions and the 2 °C target pathways in the short- to mid- term.

It is also important to note one of the missing discussions in the international negotiation process: namely, that in the Kyoto Protocol, policy makers paid attention mainly to emissions reductions of the basket of GHGs which are Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbon (HFCs), Perfluorocarbon (PFCs), Sulphur hexafluoride (SF_6), and Nitrogen trifluoride (NF_3). However, policy makers did not sufficiently consider integrated analyses on the co-benefits between GHG mitigations and air pollution reductions, ozone layer protections, and other domestic objectives in the context of sustainable development. Researchers on global emissions reduction analyses have already pointed out the co-benefits in reducing both GHGs and air pollutants emissions such as Sulphur dioxide (SO_2), Nitrogen oxide (NO_x) [13] and the important role of reducing Short-lived Climate Pollutants (SLCPs) such as Black Carbon (BC), CH_4 in achieving the 2 °C target [14]. However, these findings were not well placed on the agenda in the international negotiation process. Especially in the rapidly developing Asian countries, high concentrations of air pollution have been one of the most serious and major environmental risks to health on the local scale, and exposure to outdoor air pollutants is beyond the control of individual efforts without taking mitigation actions both at the national, regional and international levels. Thus, attention has been drawn to reducing air pollutants as a part of the political agenda in Asia.

As for GHG stabilization scenarios, there are various pathways toward the 2 °C target scenarios [7], depending on the level of peaking-out of global GHG emissions in the short-term [15] and the use of negative CO_2 emissions measures in the long-term [16]. A set of well-known GHG emissions pathways with a "likely" (greater than 66%) chance of staying below 2 °C compared to pre-industrial levels reported by UNEP [17] indicated that the median global total GHG emissions in the range of the 2 °C target with a likely probability shows a 45% reduction (range 35-55%) in 2050 below the 1990 levels of 36.6 Gt CO_2 eq. Thus, a discussion on achieving the 2 °C target is equivalent to achieving a 50% global GHG mitigation target in 2050. In order to achieve the target, mitigation measures such as energy efficiency improvement in the demand sectors and the shift to less-carbon intensive or non-fossil fuel energies in the supply sector play very important roles. These measures can also greatly reduce SLCPs and air pollutants, especially in rapidly developing countries in Asia such as China, India and the ASEAN nations. However, the effects of the co-benefits of achieving a low-carbon society in Asia have not been discussed carefully. Thus, this study analyses the mitigation potentials of SLCPs and air pollutants due to the effects of achieving a low-carbon society in Asia by 2050.

This study focuses on the following points:

- An estimation of technological mitigation potentials and costs of the Kyoto basket of GHGs such as CO_2, CH_4, N_2O, HFCs, PFCs and SF_6;
- An assessment of the co-benefit reductions of SLCPs (BC, CH_4) and air pollutants (SO_2, NO_x, PM2.5) in Asia due to the effects of mitigation measures for achieving the 2 °C target.

METHODS

This section is organized as follows. The first two sub-sections present the framework of this study, definitions and coverage of target regions, sectors and gases. The next two sub-sections provide assumptions of socio-economic drivers and future service demands and explanations of technology database and energy database. The last subsection provides scenario settings that are designed to cover the objectives of this study.

Overview of model description

This analysis consists of three parts:

- Setting future socio-economic growths by macro-economic model;
- Estimating future service demands by service demand models;
- Analyzing combinations of mitigation options by using a technology bottom-up model, named the AIM/Enduse model.

Figure 1 shows an overall picture of these three-step analytic flows and modelling framework.

As for socio-economic variables about population and GDP, this study uses the Shared Socioeconomic Pathways (SSPs) [30]. SSPs are described in the following sections in this paper. Based on settings of population and GDP in SSPs, by using service demand models such as steel production and trade model, transport demand model, municipal solid waste model, the future service demands in each service and sector are estimated in order to evaluate the future levels of driving forces for emitting GHGs, SLCPs and air pollutants at the regional and global levels. After estimating future service demands, this study evaluates selections of technology options to meet with the estimated future service demands and analyses effects of mitigation options, by using the AIM/Enduse (Global) model which is a bottom-up optimization model with detailed technology selection framework. In the AIM/Enduse model, technologies are selected in a linear optimization framework where the total system cost is minimized under several constraints such as satisfaction of service demands, availability of energy and material supplies, and other system constraints. The total system costs include initial costs, operating costs of technologies, energy costs, taxes and subsidies and other costs. The AIM/Enduse model is a recursive dynamic model which can simultaneously perform calculation for multiple years, and can analyse various scenarios, including policy countermeasures such as taxes, subsidies, and policy regulations. The AIM/Enduse model firstly estimates the final energy consumption in the final demand sectors, and next estimates the primary energy consumption for the energy supply sector, in order to meet the balance between energy demand and supply simultaneously. Finally, the model estimates emissions of GHGs, SLCPs and air pollutants based on calculated final energy consumption, primary energy consumption and non-energy demands. Detailed formulations of the AIM/Enduse model [18] and service demand models in the industry sector [19] and other sectors such as buildings and transport [20] are described in previous papers.

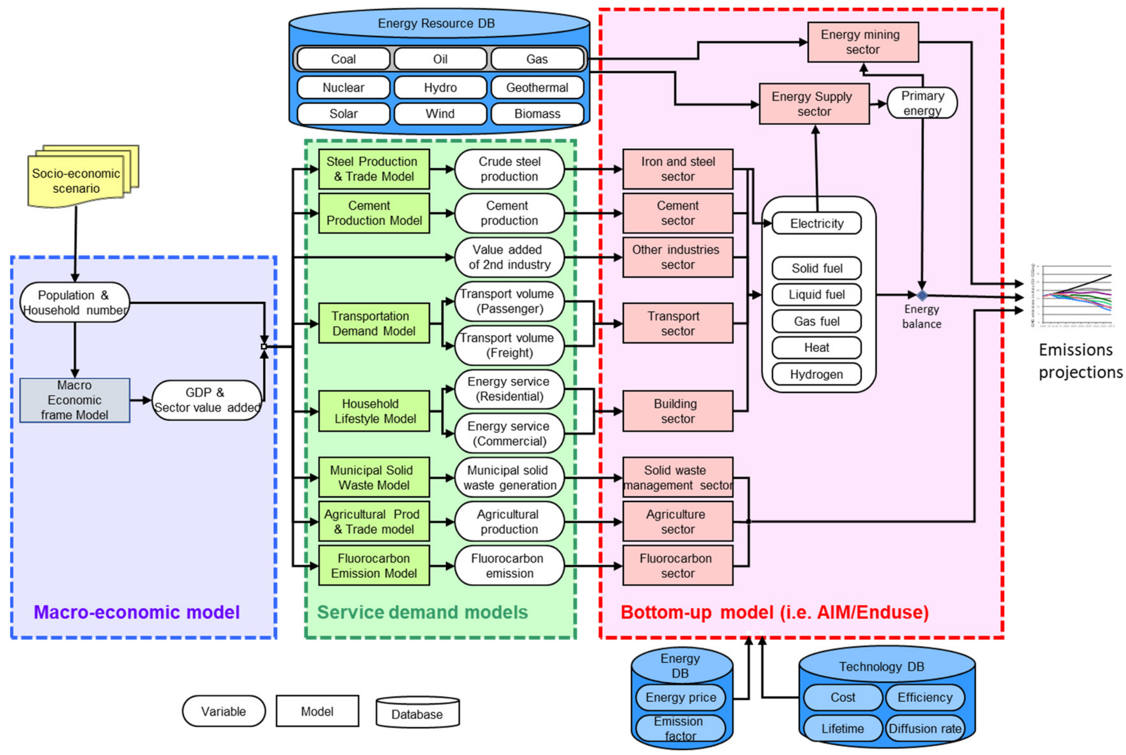

Figure 1. Overview of modelling framework in this study

Definitions of target regions, sectors and gas

The AIM/Enduse (Global) model covers 32 of the world's geographical regions, which can be also aggregated into Annex I and Non-Annex I in the Kyoto Protocol, as shown in Table 1. This study especially focuses on Asia in detail such as Japan, China, India, the ASEAN nations, and the Asian regions are classified into 12 regions (JPN, CHN, IND, IDN, KOR, THA, MYS, VNM, XSE, XSA, XEA, and XCS), as listed in Table 1.

As for the target gases, this study covers not only long-lived GHGs such as CO_2, N_2O, CH_4, HFCs, PFCs, SF_6 regulated under the Kyoto Protocol, but also SLCPs such as CH_4, BC, air pollutants such as SO_2, NO_x, Particulate Matters ($PM_{2.5}$, PM_{10}), Organic Carbon (OC), Carbon monoxide (CO), Mon-methane Volatile Organic Compounds (NMVOC), Ammonia (NH_3), and ozone depleting substances such as Chlorofluorocarbons (CFCs) and Hydro-chlorofluorocarbons (HCFCs) which are also long-lived GHGs. One caveat is that this model focuses on anthropogenic emissions in order to analyse technological mitigation measures, thus emissions from natural sources are out of scope in this study.

In order to analyse anthropogenic emissions of GHGs, SLCPs and air pollutants, this study covers major emission sources of multiple sectors such as energy supply, industry, residential and commercial, transport, agriculture, waste, industrial process, and fuel mining as listed in Table 2. However, there are some sectors which are not easy to be considered independently due to the lack of data availability in the world regions. For such cases, these sectors are aggregated into "other sectors", for example, other industries, other residential and commercial, etc., by using international energy statistics in OECD [21] and non-OECD [22]. For another example, energy-related CO_2 emissions in agriculture, fishing, and other non-specified sectors reported in international statistics by International Energy Agency (IEA) are difficult to be estimated in the future due to the lack of detailed data and its uncertainty in the world regions. Thus, this study treats these sectors as "non-specified other sectors", and calibrates GHG and air pollutants emissions in the range of emissions in the base year reported by several emission inventories such as energy-related CO_2 in the world regions [23], GHGs in the world regions [24], non-CO_2 in the Asian regions [25], and GHGs in Annex I countries [26].

Table 1. 32 global regional classification in this study: code and definition

Code	Country			Code	Country	
JPN	Japan	Annex I		CAN	Canada	Annex I
CHN	China	NonAnnex I		USA	USA	Annex I
IND	India	NonAnnex I		XE15	EU-15 in Western Europe	Annex I
IDN	Indonesia	NonAnnex I	ASEAN	XE10	EU-10 in Eastern Europe	Annex I
KOR	Korea	NonAnnex I		XE2	EU-2 in Eastern Europe	Annex I
THA	Thailand	NonAnnex I	ASEAN	TUR	Turkey	Annex I
MYS	Malaysia	NonAnnex I	ASEAN	XEWI	Other Western Europe in Annex I	Annex I
VNM	Viet Nam	NonAnnex I	ASEAN	XEEI	Other Eastern Europe in Annex I	Annex I
XSE	Other South-east Asia	NonAnnex I	ASEAN	XENI	Other Europe	NonAnnex I
XSA	Other South Asia	NonAnnex I		RUS	Russia	Annex I
XEA	Other East Asia	NonAnnex I		MEX	Mexico	NonAnnex I
XCS	Central Asia	NonAnnex I		ARG	Argentine	NonAnnex I
XME	Middle East	NonAnnex I		BRA	Brazil	NonAnnex I
AUS	Australia	Annex I		XLM	Other Latin America	NonAnnex I
NZL	New Zealand	Annex I		ZAF	South Africa	NonAnnex I
XOC	Other Oceania	NonAnnex		XAF	Other Africa	NonAnnex I

Table 2. Coverage of sectors in this study

Sector	Details
Energy supply	Coal power plant, oil power plant, gas power plant, renewable (wind, biomass, photovoltaic), nuclear, hydro, geothermal, heat
Industry	Iron and steel, cement, other industries (boiler, motor, etc.)
Transport	Passenger vehicle, truck, bus, ship, aircraft, passenger train, freight train (except for pipeline transport and international transport)
Residential&Commercial	Cooling, heating, hot-water, cooking, lighting, refrigerator, TV, other equipment
Agriculture	Livestock rumination, manure management, paddy field, cropland
MSW	Municipal solid waste, waste water management
Fugitive	Fugitive emission from fuel production
Fluorocarbons	By-product of HCFC-22, refrigerant, aerosol, foams, solvent, etching, aluminum production, insulation gas, others
Non-specified others	Sub-sectors and gases which are not listed above

Assumption of socio-economic drivers and service demands

GDP and population growth are important principal drivers for estimating future service demands, and GHG emission estimates vary widely depending on the settings of the socio-economic assumptions. Thus, it is firstly important to set socio-economic drivers such as population growth rate and GDP growth rate. In this study, as for historical population and GDP time-series data, world population prospects [27] and world urbanization prospects [28] by United Nation and world development indicator by World Bank [29] are used as principal drivers to develop and determine various parameters in the service demand models. Then, for future analyses based on the developed service demand models, this study uses future population and GDP trajectories based on Shared Socioeconomic Pathways (SSPs) – a set of qualitative and quantitative narratives that described future socioeconomic conditions in order to identify socioeconomic indicators such as population, GDP and urban population share across the world regions. In SSPs, socioeconomic pathways for climate change mitigation and adaptation are translated into 5 narrative scenarios based on various challenges [30]. Each SSP narrative describes a different socioeconomic scenario of the future. This study uses SSP1 (Sustainability), SSP2 (Continuation) and SSP3 (Fragmentation) for analyses, and SSP2 is considered as "business-as-usual" world that current trends in recent decades would be continued. Future service demand projections, such as steel production, cement production, transportation volume, are estimated using sector-specific service demand models, described in the previous paper [20]. Figure 2 shows examples of GDP and population projections used in this study.

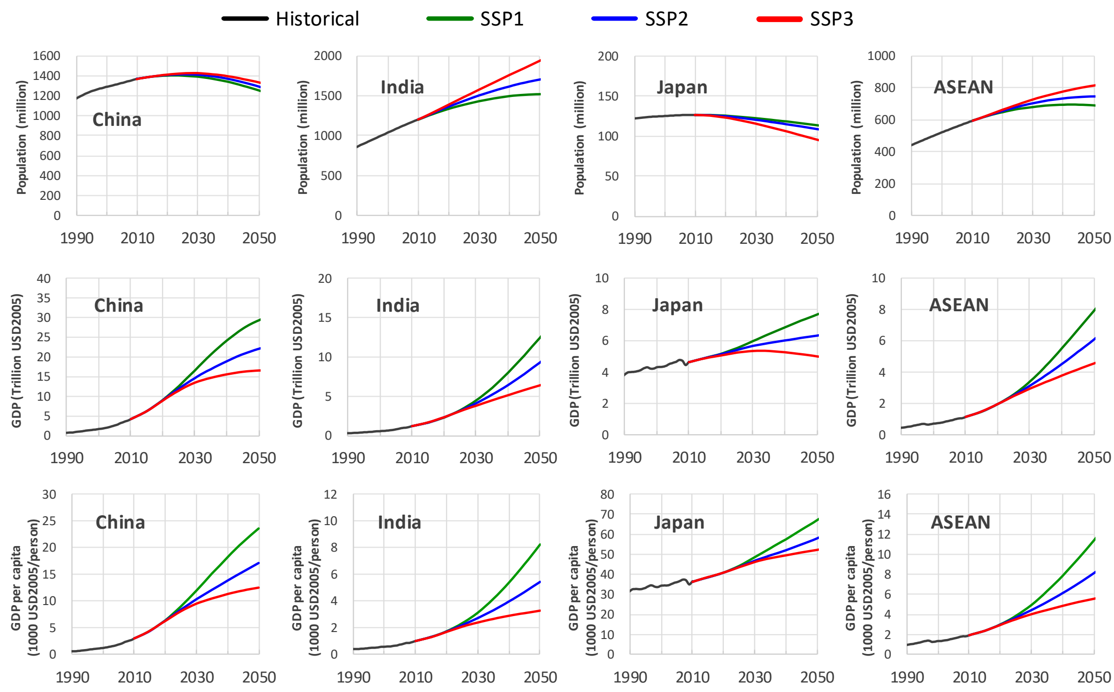

Figure 2. Socio-economic pathways used in this study in major countries/regions in Asia

Overview of technology database and energy database

The AIM/Enduse (Global) model consists of several databases such as an energy database, an energy resource database, a technology option database, and their interfaces to set various constraint conditions by energy type, sector, country and the world. In the energy database, information of emission factors and energy prices are required to set exogenously. Setting of energy prices is one of important factors for influencing on mitigation costs and affecting results of technology selection, in addition, setting of emission factors of various gases is the most important element for estimating emissions. In this study, the trend of historical energy prices in the world's regions are set based on IEA Energy Prices and Taxes [31, 32] and the range of future international energy prices in the mid-term are set based on IEA World Energy Outlook [33, 34] and IEA Energy Technology Perspective [35, 36]. Detailed domestic energy prices are set by fuel type, sector, and country in the database and their future energy prices are set under the assumption that domestic energy prices would rise in accordance with international energy prices increase. As for air pollutants, how to set emission coefficients is an important factor for estimating emissions amounts. Thus, this study considers emission coefficients of primary emissions derived from energy combustion, and emission factors of GHGs, SLCPs and air pollutants by energy source and by country were set based on various international emission factor guidelines and peer-reviewed papers [37-59].

With regard to technology options, various mitigation measures are available for promoting the introduction of energy efficient technologies on both the demand side and the supply side, as well as reducing air pollutant by air pollutant control devices. The technology option database is built based on realistic and currently existing technologies in the target sectors listed in Table 2, and the database contains approximately 500 mitigation technologies. Mitigation potentials and costs of GHGs and co-benefit reductions of SLCPs and air pollutants are analysed by using the AIM/Enduse model which is associated with the technology database. This model simulates the diffusion of mitigation technologies in the future under the criteria of total cost minimization and under several constraints, such as the satisfaction of service demand, energy resource restrictions including potentials of photovoltaic, wind and biomass supply. However, this study has some caveats. For example, one caveat is that this study takes into account all power generating sources for estimating energy consumption and CO_2 emissions, but does not consider technology mitigation options in nuclear, hydro, and geothermal power generations as decision variables, because deployment of these power sources is usually considered to be controlled not only by economic aspects but also by national policy plans designed to ensure public acceptance. Another caveat is that this technology database does not consider future innovative technologies that may or may not appear by the mid-term or long-term, due to the lack of information, for example, artificial photosynthesis, bio-fuel from algae, and thin-film photovoltaic cell options. This study also can not consider some existing technologies due to the lack of data availability such as mitigation efficiency, technology cost, for example, CO_2 mitigation options in petrochemical, N_2O mitigation options in waste water, and CO_2 mitigation options in agriculture. Local-scale technology systems such as Building Energy Management System (BEMS) and Home Energy Management System (HEMS) are also not considered due to the limitations of global scale modeling. Thus, even though an advantage of this study is that the technological feasibility of reducing GHG emissions is explicitly identified through looking at distinct technological options, this study may underestimate the future reduction potentials.

Scenario settings in this study

Various studies analysed GHG emissions pathways on the global scale to achieve the 2 °C target. This paper focuses on the following instruments:

- Imposing a carbon tax to achieve the 2 °C target level;
- Enhancing air pollutants measures for improving local air quality.

As for the air pollutant control measures, this study follows qualitative scenarios presented in SSPs. Figure 3 describes the overview of qualitative scenarios regarding enhancement levels of reduction measures both for GHGs and air pollutants. All SSPs are varieties of reference scenarios, which are sets of substitutes for the previous reference scenarios in the IPCC Special Report on Emissions Scenarios (SRES) [60]. SSP2 is the "middle of the road" reference scenario that both low-carbon measures and air control measures will be in line with the current policies. SSP1 is a more environment-oriented scenario in which air control measures will be enhanced more than the SSP2 level. On the other hand, SSP3 is the policy-failure scenario in which both low-carbon measures and air control measures will stagnate at levels less than the SSP2 level. Thus, this study quantitatively configures air pollutant measures in developing countries as being enhanced and reaching the same level as developed countries over the mid- to long-term in SSP1. In contrast, in SSP3, air pollutant measures in developing countries will stagnate at the same level as the base-year in the future.

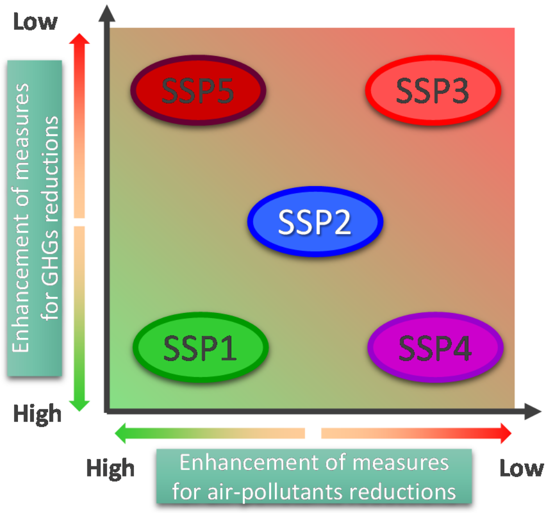

Figure 3. Scenarios for mitigation actions levels in reference scenarios based on SSPs

With regard to the level of carbon pricing, marginal abatement costs vary widely according to the variety of settings such as mitigation options, and future energy prices [61]. Imposing a high carbon tax on energy consumption largely affects results of technology selections and thus mitigation potentials. For example, in the 450 ppm scenario of International Energy Agency (IEA), which is broadly consistent with halving CO_2 emission by 2050 and achieving the 2 °C target, marginal CO_2 emission reduction costs (i.e. carbon taxes) were reported as 200-500 USD/t CO_2 in 2050 by IEA/ETP 2008 [62], 175-293 USD/t CO_2 in 2050 by IEA/ETP 2010 [63], 80-100 USD/t CO_2 in 2030 and 130-160 USD/t CO_2 in 2050 by IEA/ETP 2012 [64], and 80-100 USD/t CO_2 in 2030 and 140-170 USD/t CO_2 in 2050 by IEA/ETP 2014 [35] and IEA/ETP 2015 [36]. Hanaoka *et al.* [13] reported much higher marginal costs of around 400 USD/t CO_2 in 2050. In the short-term future, marginal CO_2 emission reduction costs considering energy policies being planned or under discussion in the Copenhagen Accord were reported as 10-30 USD/t CO_2 in 2020 by IEA/ETP 2014 [35] and IEA/ETP 2015 [36]. On the other hand, with regard to the current context of pricing a carbon emission, there are several frameworks such as emissions trading, CDM (Clean Development Mechanism) and carbon taxes. Prices of the European Unit of Accounting (EUA) under the European Union Emissions Trading Scheme (EU-ETS) and the Certified Emission Reduction (CER) under CDM projects are useful references to understand the current carbon prices, which fluctuated due to global economic change and hovered at around 15-30 EUR/t CO_2 to 10-20 EUR/t CO_2 respectively, before the start of the economic crisis in the EU. Due to the economic recession, the carbon price has declined to around 5 EUR/t CO_2. Thus, by considering the current trends and future carbon pricing estimated in previous studies, this study sets the future carbon tax scenarios as shown in Table 3. SSP1, SSP2 and SSP3 are all reference scenarios without any additional intervention for achieving a low-carbon society, thus there are no carbon tax settings. On the other hand, to achieve a low-carbon society at the level of the 2 °C target, drastic mitigation measures are required and carbon prices are high. Thus, this study sets the carbon tax at 0 USD/t CO_2 in 2015 linearly rising to a high price of 400 USD/t CO_2 in 2050 in the scenarios of SSP1 and SSP2 with GHG policy. A carbon price at 200 USD/t CO_2 in 2030 is the double of the value of penalty charges at 100 EUR/t CO_2 in the EU-ETS market, and a carbon price of 400 USD/t CO_2 in 2050 is within the range of previous studies.

Table 3. Settings of carbon taxes for achieving a low-carbon society and settings of levels of air-pollutant control measures for improving local air quality

Scenario name	2010	2015	2020	2030	2040	2050	Air pollution measures
Reference: SSP1	0	0	0	0	0	0	High
Reference: SSP2	0	0	0	0	0	0	Medium
Reference: SSP3	0	0	0	0	0	0	Low
SSP1 with GHG policy	0	0	100	200	300	400	High
SSP2 with GHG policy	0	0	100	200	300	400	Medium

Unit: USD/t CO_2 eq

RESULTS

This section is divided into two discussion parts. The first sub-section focuses on comparing emission projections of CO_2, SLCPs and air pollutants in Asia and discusses effects of the co-benefit reductions of SLCPs and air pollutants in Asia due to taking low-carbon mitigation actions. The latter sub-section analyses sectoral emission reduction potentials in order to understand major differences by sector and by scenario.

Comparisons of emissions of Carbon dioxide, Short-Lived Climate Pollutants and air pollutants in Asia

Figure 4 shows the total emissions in the Asia regions regarding CO_2, SLCPs (i.e. CH_4 and BC), and representative air pollutions, such as SO_2, NOx, $PM_{2.5}$. CO_2 emission in all reference scenarios increases emissions and the emission pathways are far from the scenario of a low-carbon society in Asia. However, GHG policy scenarios, which impose high carbon taxes linearly rising up to 400 USD/t CO_2 in 2050 to achieve the 2 °C target level, could cut CO_2 emission in Asia by half in 2050 compared to the 2010 level. In the face of such drastic CO_2 reduction scenarios, emissions pathways are not much affected by the difference of the corresponding reference scenarios. With regard to SO_2, NO_x, $PM_{2.5}$ as representative air pollutants and BC as a representative SLCP, emissions in SSP1 will decrease more than SSP2 after 2030 due to the effects of enhancement of air pollutant control measures in developing countries.

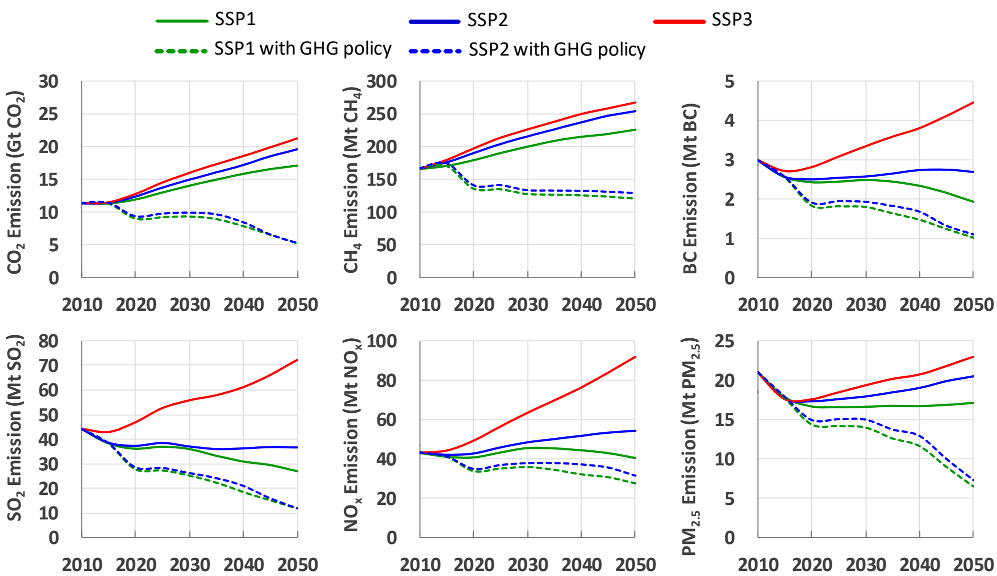

Figure 4. Scenarios for mitigation actions levels in reference scenarios based on SSPs

On the other hand, because air pollutant control measures in developing countries are stagnated as the same level as the base-year, emissions in SSP3 will increase largely in accordance with the increase of service demands. GHG policy scenarios can largely reduce emissions of SO_2, NO_x, $PM_{2.5}$, and BC, thus it is important to emphasize effective co-benefits in reducing air-pollutions and SLCPs while taking mitigation actions to achieve a low-carbon society. The total emissions of CO_2, CH_4, BC, SO_2, NO_x, and $PM_{2.5}$ are largely reduced from SSP2 to SSP 2 with GHG policy at the levels of 14.4 Gt CO_2, 125.4 Mt CH_4, 1.6 Mt BC, 24.4 Mt SO_2, 22.6 Mt NO_x, and 13.2 Mt $PM_{2.5}$ in 2050, which correspond to around 54%, 23%, 63%, 73%, 27% and 65% reductions as compared to the emission levels in 2010.

Figure 5 shows the emission reduction ratio in Asian regions regarding CO_2, SLCPs, and air pollutants, compared to the SSP2 level. These figures can indicate the following comparisons:

- The effects of taking measures only for air pollutant reductions (e.g., comparisons between SSP2 and SSP1, and between SSP2 with GHG policy and SSP1 with GHG policy);
- The effects of taking measures only for GHG reductions and their co-benefits in reducing air-pollution and SLCPs (e.g., comparisons between SSP2 and SSP2 with GHG policy, and also between SSP1 and SSP1 with GHG policy);
- The effects of taking measures both for GHG and air pollutant reductions (e.g., comparisons between SSP2 and SSP1 with GHG policy).

When comparing the results from SSP2 to SSP1 and the results from SSP2 to SSP2 with GHG policy, reduction ratios of air pollutants and SLCPs are much larger when due to the effects of co-benefits in drastic CO_2 reduction measures (i.e. from SSP2 to SSP2 with GHG policy) than when due to the effects of taking measures for air pollutants only (i.e. from SSP2 to SSP1). In addition, reduction ratios from SSP2 with GHG policy to SSP1 with GHG policy are smaller than the ratio from SSP2 to SSP1. Thus, air pollutant control measures become lesser effective after taking measures for drastic CO_2 reduction, because the significant energy sources of air pollutants already turn into cleaner energy sources due to effects of low-carbon measures.

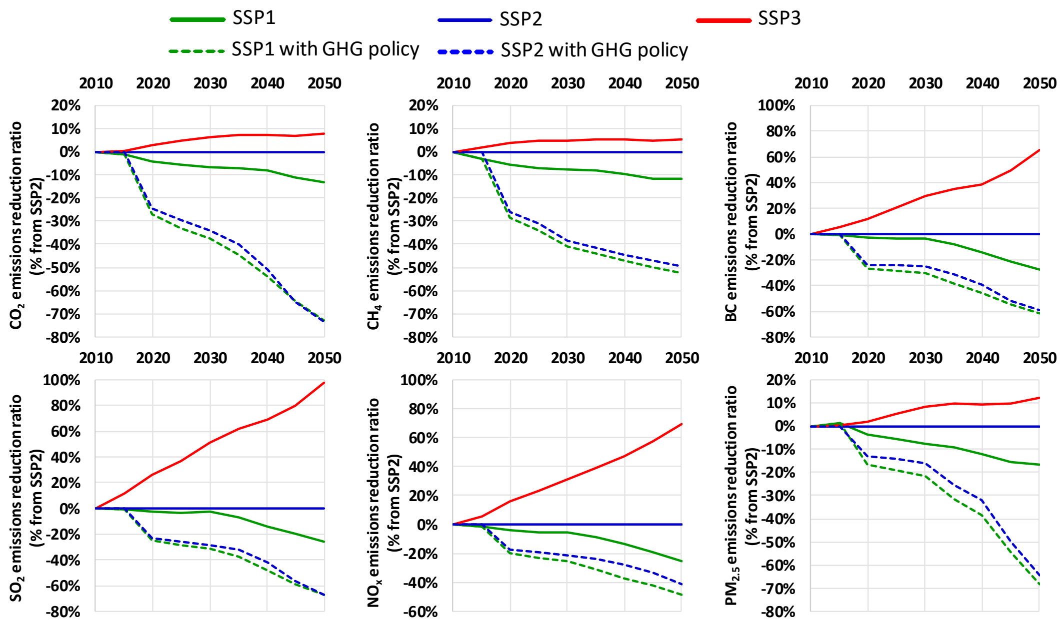

Figure 5. Reduction ratio of CO_2, SLCPs, and air pollutants, compared to the SSP2 level in Asia

SSP2 shows a "business-as-usual" world which is an extension of the current trends in recent decades and are not in line with transitions toward the 2 °C target. The international negotiation process under the UNFCCC has been running into difficulties in arriving at an international agreement on the mid-term reduction targets.

However, it is necessary to take into account comprehensive strategies to promote mitigation technologies to achieve the maximum potentials of energy savings. Careful attention to these co-benefits in reducing air-pollutions and SLCPs may become one of the steps to overcome various barriers for achieving a low-carbon society.

Sectoral analyses of emissions reduction potentials

To understand differences in the co-benefits in reducing air pollutants and SLCPs emissions through CO_2 mitigation measures, sectoral emissions of SO_2, NO_x, BC and $PM_{2.5}$ in Asia are shown in Figure 6. The figures to the left of Figure 6 show emission comparisons from SSP2 to SSP1 with GHG policy, which indicate the effects of taking measures both for GHG and air pollutant reductions, and the figures to the right in Figure 6 show emission comparisons from SSP2 to SSP1, which indicate the effects of taking measures only for air pollutant reductions. Sectoral reduction potentials in the power sector, the industry sector, the transport sector and the building sector (i.e. residential and commercial sectors) are also described in Figure 6. When it comes to reduction potentials in the case of measures only for air pollutants, profiles of sectoral reduction potentials are dispersed depending on gases because of the difference of major emission sources.

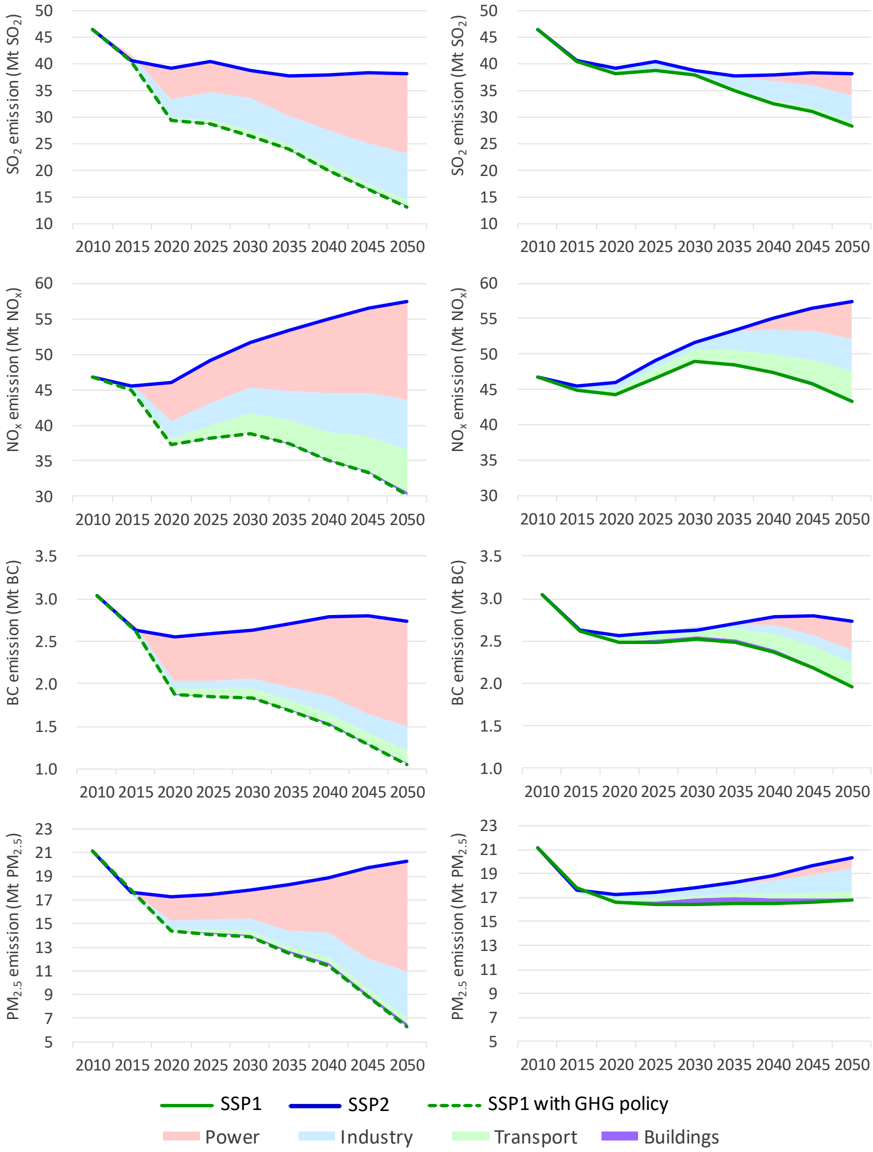

Figure 6. Sectoral emissions reductions of SO_2, NO_x, $PM_{2.5}$ and BC in Asia

However, features of sectoral reduction potentials in the case of measures both for GHG and air pollutants are different and impacts of reductions in the power sector become very large. This is because of the fuel shift from high-carbon fossil fuels to less-carbon intensive fuels or renewable energies and the improvement of energy efficiency, and thus the significant energy sources of air pollutants turn into cleaner energy sources. These low-carbon measures in the power sector greatly contribute to reducing emissions of SO_2, NO_x, BC and $PM_{2.5}$. In addition, with regard to NO_x, major sectoral sources derive from the transport sector as well as the power and industry sectors, thus, the shift from gasoline/diesel vehicle to efficient vehicles such as hybrid electric vehicles, plug-in hybrid vehicles, and electric vehicle will be also effective.

The building sector is one of major sectoral sources of BC and $PM_{2.5}$ emissions in the historical inventory in Asia, due to consumption of low-efficient energy sources such as traditional biomass and coal [25]. However, mitigation potentials of BC and $PM_{2.5}$ are not mainly observed in Figure 6. This is because, even in reference scenarios of SSP2 and SSP1, this study assumed the increase of electrification in the building sector with high economic growth in the Asian developing countries. A certain amount of biomass and coal would be already shifted to other energy sources in reference scenarios. As a result, the building sector does not become a measure sector which has mitigation potentials of BC and $PM_{2.5}$. If the levels of electrification in reference scenarios are set at the similar level to the current status, mitigation potentials of BC and $PM_{2.5}$ should be more observed in Figure 6. Thus, it is important to note one caveat that the future scenario settings of the electrification ratio in the building sector will have its influence on results of emissions pathways and mitigation potentials of BC and $PM_{2.5}$.

CONCLUSIONS

By using the AIM/Enduse (Global) model which is a bottom-up optimization model with a mitigation options database of realistic and currently existing technologies, this study focused on analyses of the co-benefit in reducing air-pollutions and SLCPs while taking mitigation actions for achieving the 2 °C target. This study used reference scenarios based on SSPs, both for quantitative data about future population and GDP trajectories and qualitative storylines regarding enhancement levels of reduction measures of GHGs and air pollutants. In order to compare effects of mitigation measures, this study analysed the effects of taking measures only for air pollutant reductions, the effects of taking measures only for GHG reductions and their co-benefits in reducing air-pollutions and SLCPs, and the both effects.

One finding was that, due to CO_2 measures and their co-benefits in reducing air-pollutions and SLCPs, the total emissions of SO_2, NO_x, BC and $PM_{2.5}$ can be reduced largely at the levels of 24.4 Mt SO_2, 22.6 Mt NO_x, 1.6 Mt BC and 13.2 Mt $PM_{2.5}$ in 2050, which correspond to around 63%, 73%, 27% and 65% reductions as compared to the emission levels in 2010. Because of the fuel shift from high-carbon fossil fuels to less-carbon intensive fuels or renewable energies and the improvement of energy efficiency, these effects of reducing emissions of SO_2, NO_x, BC and $PM_{2.5}$ are much larger than effects of taking measures for air pollutants only. In addition, air pollutant control measures become lesser effective after taking measures for drastic CO_2 reduction, because the significant energy sources of air pollutants already turn into cleaner energy sources due to effects of low-carbon measures. In order to cut CO_2 emission in Asia by half in 2050 compared to the 2010 level which is broadly consistent with achieving the 2 °C target, the level of carbon tax is quite expensive at 400 USD/t CO_2 in 2050. Such a high carbon price will become a barrier to arrive at an international agreement on the mid-term reduction targets in the international negotiation process under the UNFCCC. However, it is important to emphasize effective co-benefits in reducing air-pollutions and SLCPs while taking mitigation actions for achieving the low-carbon society, and these co-benefits may become one of the steps to overcome various barriers for achieving a low-carbon society.

It is important to note some caveats that this study took into account realistic and currently existing mitigation technologies in most of major sectors, however, could not consider some existing technologies and also future innovative technologies that may appear, due to the lack of data availability such as mitigation efficiency, technology cost in the world regions. In addition, local-scale technology systems such as BEMS, HEMS and electricity smart grid supply systems are not considered due to the limitation of global scale modelling. It is also necessary to note the varieties of future scenarios settings about the socio-economic assumptions and some key constraints, which have influences on emissions pathways and mitigation potentials. Thus, even though an advantage of this study is that the technological feasibility of reducing emissions of GHGs, SLCPs and air pollutants is explicitly identified through looking at distinct technological options, this study may underestimate or overestimate the future reduction potentials. These limitations are the next challenge to overcome for further analysis and show uncertainty ranges of co-benefits in reducing SLCPs and air pollutants while achieving the 2 °C target.

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