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COBENEFITS AND INVESTMENT COSTS OF ALTERNATIVE DECARBONIZATION PATHWAYS TOWARD 2 DEGREE TARGETS IN CHINA AND INDIA

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ABSTRACT

This study analyzes emissions projections of CO_2, air-pollutants and short-lived climate pollutants (SLCPs) in China and India due to various combinations of low-carbon and air pollutants control measures, and evaluates the required additional investment costs of combinations of measures as well as the cobenefits in reducing air pollutants in response to low-carbon measures for achieving a 2 °C global temperature change limit above pre-industrial levels, so-called "2 °C target".

It was found that, even if combinations of low-carbon and air pollution control measures are different, there are similar CO_2 emission projections for achieving the 2 °C target. However, different combinations of these measures make major effects on diverse emission projections of air pollutants and BC. It is because major emission sources of air pollutants and BC are diverse in different technologies in different sectors. In addition, investment costs of end-of-pipe measures are cheaper than low carbon measures. As a result, depending on combinations of low-carbon and air pollution control measures, required additional investment costs are different. The lower carbon measures are taken, the more energy shifting occurs to renewables and the more additional investments are required. However, emission sources of air pollutants and BC are reduced and thus there will be less need for introducing end-of-pipe measures for air pollutants. It is important to highlight such cobenefits from the viewpoint of reducing both emission amounts of air pollutants and BC and investment costs.

Keywords: Short-Lived Climate Pollutant, Air Pollutant, Electrification, Energy Shift, Removal Technology, Additional Investment Cost

1. INTRODUCTION

In Asian developing countries, especially China and India, due to the rapid development over the past decades, they have been facing with serious air pollution [1]; at the same time, China and India became major emitters of CO_2 in the world [2]. In order to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels" (so-called "2°C target") in the Paris Agreement adopted by the United Nations Framework Convention on Climate Change (UNFCCC) Parties, it is required for all UNFCCC parties to reduce GHG emissions drastically, much further efforts than national determined reduction targets by 2030 [3]. However, additional efforts on reducing GHGs require investment on low-carbon measures, and its investment becomes as one of major barriers for deployment of mitigation measures. Meanwhile, it is necessary to pay attention to the cobenefits in reducing air pollutants in response to low-carbon measures. Moreover, it is also important to consider drastic short-lived climate pollutants (SLCPs) reductions, because the United Nation Environment Programmed (UNEP) reported that the reductions of SLCPs concentrations in the atmosphere, such as black carbon (BC), and tropospheric ozone (O_3), Methane (CH_4) offer an opportunity to reduce the rate of global warming over the next two to four decades if maximum measures for reducing SLCPs are implemented globally by 2030 [4]. This means that early action on reducing SLCPs may have the potential to help achieving the 2 °C target, rather than only taking reduction efforts for GHG emissions.

Li et al evaluated air quality improvement cobenefits of low carbon measure [5] and also assessed energy-water relations by considering energy system

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transformation [6], when achieving the 2°C target in China. Mittal et al assessed a difference of economic impacts between the 2°C and 1.5°C targets in India [7], and Dai, et al discussed impacts of the 2°C target global policies to CO_2 mitigation potentials and costs comparing in China and India [8]. However, there are various pathways to reduce CO_2 emission equivalent to the 2°C target level in China and India. In addition, emissions of air pollutants and SLCPs in China and India will vary depending on different combinations of CO_2 mitigation measures, which are hot topics form the viewpoint of local climate impact and health impact. Different combinations of mitigation measures will also have an affect on results of investment cost, and it helps to discuss economic cobenefits of low carbon measures.

Therefore, the main research target of this study is to analyze alternative decarbonization pathways toward the 2°C target and compare similarities and differences between China and India. This study particularly focuses on the following three issues in China and India; 1) to evaluate synergies and trade-offs of various combinations of low-carbon measures and air pollutants control measures, 2) to evaluate required additional investment costs of different combinations of these mitigation measures and 3) to analyze cobenefits of potential emission reductions of air pollutants and SLCPs due to low-carbon measures toward the 2 °C target.

2. METHOD

2.1 Overview of model description and approaches

In order to analyze future emissions projections, mitigation potentials and costs by combinations of various kinds of technologies, this study uses a technology bottom-up model with a detailed technology selection framework, named the AIM/Enduse model. The AIM/Enduse model is a partial equilibrium, recursive dynamic optimization model, to minimize the total system costs including initial cost, operation and management cost, energy cost, carbon tax, energy tax, subsidy. AIM/Enduse can set various constraints such as energy and material supply, service demand, technology deployment, emissions, by region, sector, energy type and gas type. Its optimization algorism, all equations and definitions, and available constraints are described in the AIM/Enduse model manual [9].

AIM/Enduse evaluates technology selections from the technology database, to fully comply with the future service demands and balance energy supply and demand sectors endogenously. In order to analyze future GHGs and air pollutants projections by using AIM/Enduse, future service demands are firstly required to be set in AIM/Enduse exogenously. To determine future service demands, this study uses future socio-economic assumptions and variables such GDP, population and urbanization in China and India, based on the Shared Socioeconomic Pathways (SSPs) [10]. Next, future service demands by sector are estimated by using sector-wise service demand models developed in the previous study [11], such as crude steel, cement, passenger transport, freight transport. By combining service demand models and AIM/Enduse model, this study analyzes multiple sectors such as energy supply, industry, transport, residential and commercial, agriculture, waste, and non-specified others. As for the target gases, this study covers not only long-lived GHGs such as CO_2, Nitro oxide (N_2O), CH_4, Hydrofluorocarbon (HFC), Perfluorocarbon (PFC), sulfur hexafluoride (SF_6) regulated under the Kyoto Protocol, but also SLCPs such as CH_4, BC, air pollutants such as sulfur dioxide (SO_2), Nitro oxide (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.

2.2 Assumptions of data and scenario

Combinations of mitigation options can cause both synergies and trade-offs, because the reduction effects of different measures vary depending on the type of energy and targeted gas. This study considers hundreds of various mitigation technology options among multi-sectors, and those mitigation options can be classified into the following four groups; 1) End-of pipe (EoP) measures to recover/reduce a specific emission directly at emission sources, 2) improvement of quality of fuel, 3) deployment of energy efficient technologies, 4) fuel-shift from high-carbon fossil fuels to less-carbon intensive fuels or renewables. Overview of mitigation technologies and these groups are summarized in Table 1.

Detailed domestic energy prices in the base year are set by fuel type, sector in China and India, and their future energy prices are set by considering the trend of historical energy prices and the range of future international energy prices in the mid-term are set based on IEA statistics and outlook reports. Emission coefficients of primary emissions derived from energy combustion are considered and thus emission factors of GHGs, SLCPs and air pollutants are set by energy source and by country based on various international emission guidelines and peer-reviewed papers. However, the

Table 1 Overview of mitigation technology groups

Group	Description	Examples
Group 1	Measures to install removal equipment and recovery equipment at emission sources and directly reduce a specific emission	Desulfurization equipment, denitrification equipment, dust collecting equipment, CO_2 capture and storage (CCS), facilities for gas recovery from landfill disposal sites, etc.
Group 2	Measures to reduce emissions by improving the quality of fuel	Shifting from low-quality (i.e. high sulfur content) fuel to high-quality (i.e. low sulfur content) fuel.
Group 3	Measures to reduce emissions by reducing energy consumption through the deployment of energy-efficient technologies or regulations	High-efficieny power plants, high-efficiency boilers and furnaces, high-efficiency vehicles, high-efficiency home appliances, etc.
Group 4	Measures to reduce emissions by fuel-shifts from high-carbon fossil fuels to less-carbon intensive fuels or renewable energies	Energy shifts from coal-fired power to solar and wind power, fuel-switches from fossil fuel to hydrogen fuel in vehicles, promoting electrification rates to replace fuel combustion with electricity in demand sectors, etc.

Table 2 Scenario Matrix of this study [3]

Scenario Group	Scenario code	Major combinations of mitigation measures on GHGs, air pollutants and SLCP					
		EoP enhancement (EoP)	2°C target measures (2D)	CO_2 Enhancement (CCS)	Renewable enhancement (RES)	Electrification enhancement in buildings (BLD)	Electrification Enhancement in transport (TRT)
Reference	Ref						
End-of-pipe only	EoPmid	Mid					
	EoPmax	Max					
2°C target & End-of-pipe	2D-EoPmid-CCSBLD	Mid	✔	✔		✔	
	2D-EoPmid-RESTRT	Mid	✔		✔		✔
	2D-EoPmid-RESBLDTRT	Mid	✔		✔	✔	✔
	2D-EoPmax-RESBLDTRT	Max	✔		✔	✔	✔

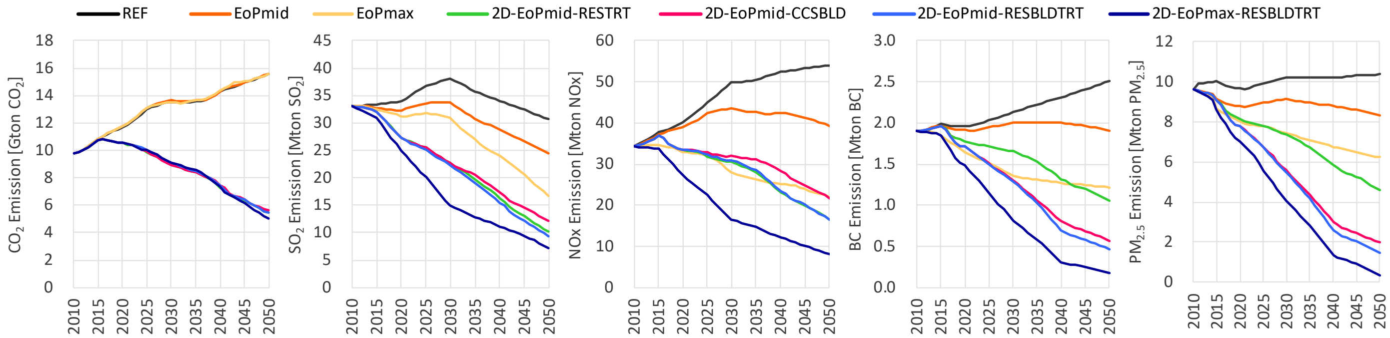


Fig1 Total emissions projections combined of China and India

range of emission factors vary widely depending of gas and energy types. Thus this study conducts the base-year emission calibration by comparing with well-known international emissions inventories in Asia, named EDGER, HTAP and REAS. The detailed data sources of energy prices, emission factors and emission inventories are described in the previous study [12].

This study aims to analyze alternative decarbonization pathways toward the 2°C target and evaluate impacts on cobenefits and required additional investment costs due to various combinations of low-carbon measures and air pollutants control measures. Thus, this study selects 7 scenarios which were proposed in the previous study [13], from the viewpoint of wide variety of emissions projections of air pollutants and SLCPs. Overview of scenario matrix is summarized in Table 2. Different level of enhancement policies are considered for EoP measures and effective decarbonization measures. Electrification is currently one of remarkable policy measures, combining with renewable energy or fossil fuel with CCS. Thus, this study carefully focuses on more enhancement of these specific measures in the 2°C target.

3. RESULTS AND DISCUSSIONS

3.1 Emissions Projections of CO_2, air pollutants and BC

Figure 1 shows the total emission projections combined of China and India, regarding CO_2, major air pollutants (SO_2, NOx, $PM_{2.5}$) and BC as one of SLCPs.

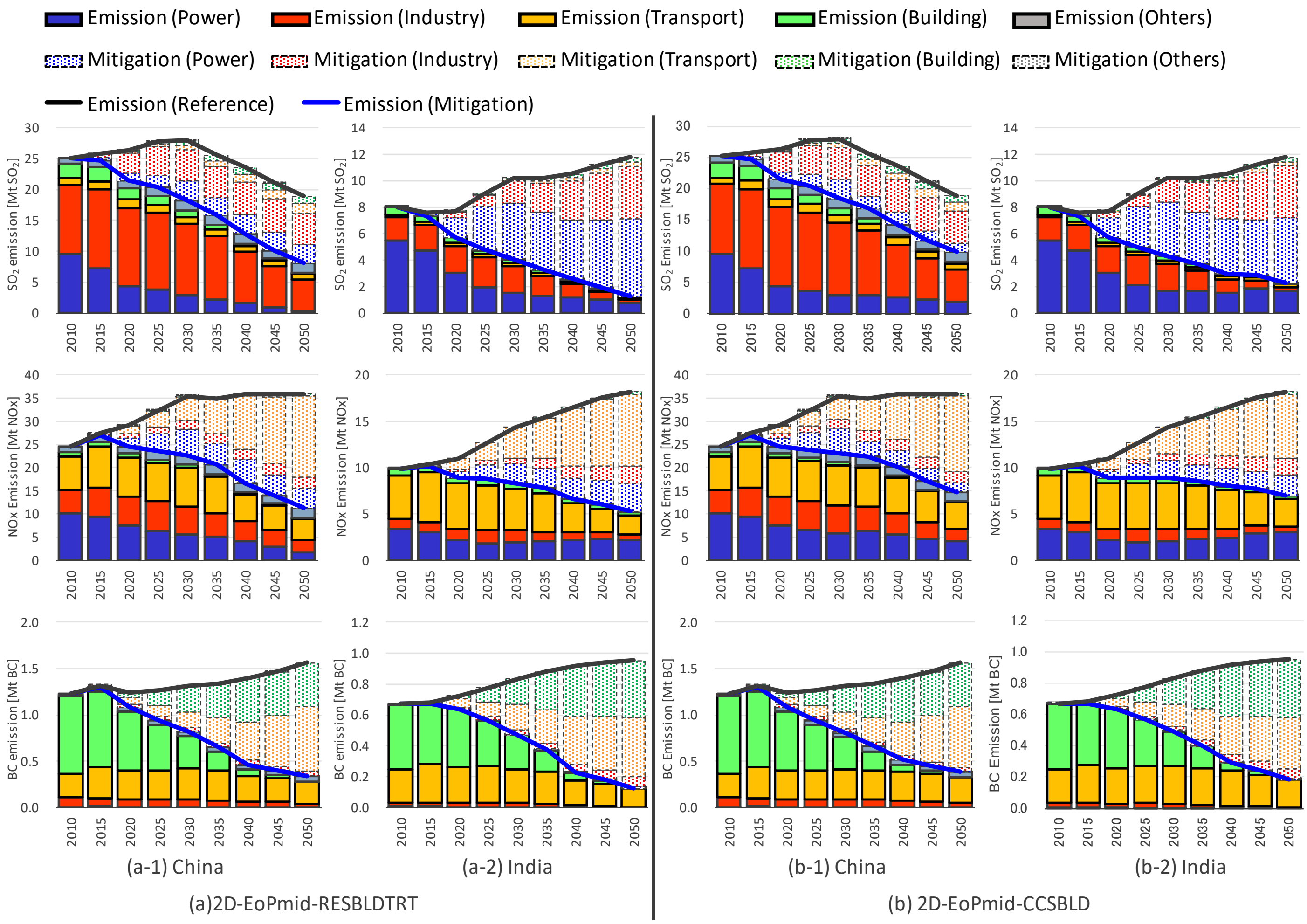
As for *EoPmid* and *EoPmax* scenarios, these CO_2 emission projections are almost the same as the REF scenario; this is because *EoPmid* and *EoPmax* only consider diffusions of end-of-pipe measures for reducing air pollutants, but don't consider any low carbon policies. However, emission projections of air pollutants and BC vary widely between *REF*, *EoPmid* and *EoPmax*; this is because levels of diffusions of end-of-pipe measures are largely different.

As for all 2D scenarios, CO_2 emission projections are similar, even if combinations of low carbon measures are different; for example, decarbonization of the energy mix in the power sector is very different between *2D-EoPmid-RESBLDTRT* and *2D-EoPmid-CCSBLD*. However, it is important to highlight that emission projections of air pollutants and BC in 2D scenarios vary widely, because major emission sources of air pollutants and BC are diverse in different technologies in different sectors. It indicates that, depending on combinations of low carbon measures, the level of investment costs and cobenefits in reducing air pollutants and BC.

3.2 Mitigation potentials by sector

Figure 2 shows sector-wise emissions projections and mitigation potentials in China and India, respectively, for example SO_2, NOx, and BC emissions. Sector-wise mitigation potentials are calculated by comparing mitigation scenarios of *2D-EoPmid-RESBLDTRT* and *2D-EoPmid-CCSBLD* with *REF* scenario.

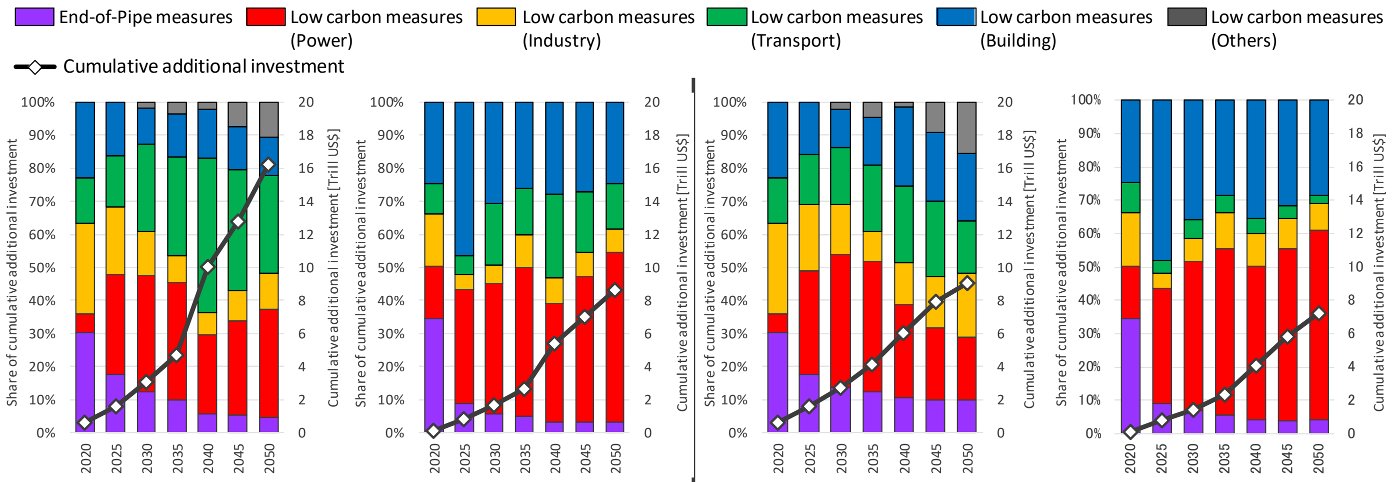
Major emission and mitigation sectors are power and industry sectors for SO_2, transport and power sectors for NOx, and building and transport sectors for BC. Thus, if renewable energy such as solar and wind is enhanced in preference to coal-fired power generation with CCS in power sector (i.e. shifting from *2D-EoPmid-CCSBLD* to



(a-1) China (a-2) India (b-1) China (b-2) India

(a)2D-EoPmid-RESBLDTRT (b) 2D-EoPmid-CCSBLD

Fig2 Sector-wise emissions projections and mitigation potentials in China and India



(a-1) China (a-2) India (b-1) China (b-2) India

(a)2D-EoPmid-RESBLDTRT (b) 2D-EoPmid-CCSBLD

Fig3 Cumulative additional investment

2D-EoPmid-RESBLDTRT), there are more cobenefits of reducing SO_2 and NOx.

If the intensiveness of the electrification rate in transport sector is accelerated by combination with enhancement of renewable energies (i.e. shifting from *2D-EoPmid-CCSBLD* to *2D-EoPmid-RESBLDTRT*), there are more cobenefits of reducing NOx and BC. If the intensiveness of the electrification rate in building sector is accelerated by combination with enhancement of renewable energies (i.e. shifting from *2D-EoPmid-CCSBLD* to *2D-EoPmid-RESBLDTRT*), there are more cobenefits of reducing BC, because especially rural residential sector largely relies on traditional biomass which is the major source of BC.

3.3 Comparison of investment costs

Figure 3 shows additional investment costs in China and India. These figures indicate share of sector-wise cumulative investment costs and the total cumulative investment costs up to 2050. Additional investment costs are calculated by comparing scenarios of *2D-EoPmid-RESBLDTRT* and *2D-EoPmid-CCSBLD* with *REF* scenario.

Combinations of low-carbon measures and results of mitigation potentials are different between *2D-EoPmid-CCSBLD* and *2D-EoPmid-RESBLDTRT*, thus additional investment costs are also different. Investment costs of end-of-pipe measures are cheaper than low carbon measures. It indicates that if only aim to reduce a specific air pollutant such as SO_2, NOx, $PM_{2.5}$, BC, it is cost effective to introduce only end-of-pipe measures. However, for both achieving decarbonization to the 2 degree target level and reducing environmental impacts due to air pollutants, combinations of low carbon measures and end-of-pipe measures must be required.

The more low-carbon measures are taken, the more energy shifting will occur from fossil fuels to renewables. As a result, emission sources of air pollutants and BC are reduced and there will be less need for introducing end-of-pipe measures. For example, costs of renewables in power and electric vehicles in transport are more expensive than coal with CCS in power and traditional engine vehicles in transport, this is why EoP investments become smaller in *2D-EoPmid-RESBLDTRT* than *2D-EoPmid-CCSBLD.* Additional investment costs in *2D-EoPmid-RESBLDTRT* is higher than *2D-EoPmid-CCSBLD*, however, there are larger cobenefits in reducing air pollutants and BC in *2D-EoPmid-RESBLDTRT*.

4. CONCULUSIONS

This study evaluated synergies and trade-offs of various combinations of low-carbon and air pollutants measures in China and India, for achieving the 2°C target level, and analyzed emissions projections of BC and air pollutants and their additional investments. Different combinations of low-carbon measures make effects on diverse emission projections of air pollutants and BC as well as different additional investments. Promoting low carbon measures especially shifting to renewables will require more additional investments, however can gain more cobenefits in reducing air pollutants and BC. In addition, if electrification policies are enhanced more in residential, commercial and transport sectors, it produces more synergy effects of reducing both air pollutants and SLPC.

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