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Co-benefits of air pollution control and climate change mitigation strategies in Pakistan

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ABSTRACT

Pakistan's urban air pollution is among the world's worst, wreaking havoc on public health and the economy. Although the country's environmental protection act and the climate change act recognize the dual challenges of air pollution and climate change, it lacks an integrated national strategy to manage both simultaneously. Based on simulations with the GAINS model (an integrated assessment model) through soft coupling with the EnerNEO Pakistan model (an energy-economic model), we assess the benefits of climate policies and air pollution control measures on air quality and public health for Pakistan under the baseline and alternative scenarios. Our results reveal that Pakistan's current air pollution control measures are insufficient to meet the country's air quality standards under the baseline scenario. Implementing sustainable development strategies will reduce nationwide $PM_{2.5}$-related mortalities by 24% in 2050 compared to the baseline. While advanced control measures have the potential to improve air quality and human health in Pakistan, when combined with national sustainable development strategies, they have the potential to halve greenhouse gas emissions (implementing SDG 13 indicator on climate action) and save on emission control costs approximately by a quarter (0.32% of GDP) by 2050. This appears to be a significant co-benefit in terms of air quality (environmental), health (social), and cost (economic), implying that Pakistan's future policymaking should prioritize cost-effective co-control of air pollution and greenhouse gases.

1. Introduction

Air pollution is the world's fifth-largest mortality risk factor. Over 90% of the world's population lives in places where the World Health Organization's (WHO) recommended guidelines for healthy air is exceeded (HEI, 2019). Epidemiological studies in Asia and the Pacific show that $PM_{2.5}$ and ground-level ozone exposures contribute significantly to disease burden (UNEP, 2019). In 2017, South Asia had the highest annual $PM_{2.5}$ exposures, implying air pollution as the second leading cause of death in the region (HEI, 2019; Gakidou et al., 2017).

Pakistan is currently dealing with both air pollution and climate change (UNFCCC, 2016). It is South Asia's second-fastest-urbanizing country (Ebrahim, 2021), ranked as the world's second-most polluted country in 2020 (IQAir, 2021). Nearly 100% of the population lives in areas where $PM_{2.5}$ concentrations surpass the WHO guideline value (5 $\mu g/m^3$) and national ambient air quality standards (NAAQS) of 15 $\mu g/m^3$, recognizing air pollution as the leading health risk factor in Pakistan in 2017 (Anjum et al., 2021; HEI, 2020). Furthermore, despite its small contribution (<1%) to global greenhouse gas (GHG) emissions, Pakistan has the highest GHG emissions intensity – total emissions divided by the gross domestic product (GDP) – among South Asian neighbors (Mir et al., 2021, 2020; Sánchez-Triana et al., 2014; Khan et al., 2011). The country set a baseline scenario target of reducing GHG emissions by 50% (15% unconditional and 35% conditional) below projected emissions in 2030 (UNFCCC, 2021), which would necessitate a transition from fossil fuels to cleaner energy sources in order to decarbonize the power system and meet the Paris climate pledges (Ebrahim, 2021). Because air pollutants and GHGs often come from the same sources, adopting an integrated approach to tackle both simultaneously can deliver important co-benefits in Pakistan (Scovronick et al., 2021; Yang et al., 2021; Purohit et al., 2019; IEA, 2016).

High levels of air pollution degrade air quality and have serious

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health impacts (UNEP, 2019; Landrigan et al., 2018; Burnett et al., 2018; Cohen et al., 2017). Although the exact number of premature deaths from outdoor air pollution in Pakistan is unclear, the scientific literature reports a wide range, ranging from 22,064 to 159,200 cases per year (HEI, 2020; Shi et al., 2018; Cohen et al., 2017; Giannadaki et al., 2016; WHO, 2016). These health implications have a substantial economic impact (welfare loss), which accounted for 5.9% of Pakistan's GDP in 2013 (World Bank, 2016). This suggest that the annual cost of ambient air pollution in Pakistan could exceed $47 billion (World Bank, 2016). Studies conducted over the last two decades found high ambient $PM_{2.5}$ concentrations (above the recently updated[1] WHO guideline value of 5 $\mu g/m^3$) in Pakistan, owing primarily to fossil fuel combustion in power, industry, and road transport, as well as solid fuel use in residential combustion (Niaz et al., 2016; Shahid et al., 2015; Alam et al., 2015, 2011; Javed et al., 2014; Khwaja et al., 2012; Colbeck et al., 2011; Raja et al., 2010; Stone et al., 2010; Lodhi et al., 2009; Biswas et al., 2008). Due to an increase in polluting industries, air quality is likely to deteriorate further in the future unless appropriate countermeasures are implemented. Nevertheless, global knowledge and experience show that air quality can be managed while minimizing socio-economic impacts. To be most effective, policies must be well-designed, prioritize cost-effective interventions for sources that deliver maximum benefits, and be well integrated with other national development goals (see Section 4.2).

This study examines the current and future air quality impacts in Pakistan under current legislation in the context of socio-economic development dynamics. Furthermore, we compare the impact of alternative pollution control strategies on health until 2050 using the Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) integrated modelling tool (Amann et al., 2011) in conjunction with the EnerNEO Pakistan energy model (EnerNEO Pakistan, 2018). The study aims to illustrate the potential for alternative policy approaches that maximize the qualitative co-benefits of air pollution management and GHG mitigation. A quantitative policy analysis, however, would require a more in-depth review of the study's input data.

Following is a breakdown of the paper's structure. Modelling tools used are introduced in Section 2. Section 3 discusses the current state of air quality in Pakistan, its drivers, and health impacts. Section 3 explores the potential impact of current and alternative energy and air pollution control policies/regulations. The costs and benefits of alternative policy scenarios are discussed in Section 4. Section 5 highlights uncertainties and limitations of the analysis and Section 6 concludes.

2. Materials and methods

2.1. Approach

This study employs an integrated multidisciplinary approach comprised of two well-established scientific modelling tools to investigate the effectiveness of various air pollution control and climate policies in Pakistan.

The EnerNEO Pakistan model (see Section 2.2.1) examines socio-economic factors that contribute to pollution, with a particular focus on the energy sector. The energy database includes three major components of the energy system: i) electricity production (excluding heat production); ii) energy use for conversion (i.e., refinery); and iii) final energy use in industry (including iron and steel plants, cement manufacturing, chemical industry, other industrial boilers, and other non-combustion processes – non-energy use of fuels sub-categories); domestic sector (including residential and commercial sectors, as well as agriculture, forestry, fishing and services sub-categories); and transport (including on-road and off-road transportation sub-categories).

These data are then fed into the GAINS model (see Section 2.2.2) to determine the efficacy of policy measures on air quality and health outcomes. Note that the activity projections for the brick industry, waste and agriculture sector were derived from the GAINS database whereas activity data for back-up generator is taken from Lam et al. (2019). The findings are based on a comparison of the following scenarios that measure the effects of various policy interventions:

- the emissions control measures already in place in 2015, and any additional policies and measures planned/adopted after 2015 (business-as-usual (BAU) scenario),
- the potential benefits from full implementation of advanced emission control measures (advanced control technology (ACT) scenario), and
- the air quality co-benefits of sustainable development measures typically taken to achieve other policy goals (sustainable development scenario (SDS)).

2.2. Modelling tools

As mentioned above, this study links two scientific modelling tools (Fig. 1): the EnerNEO Pakistan model developed by Enerdata[2] for the Government of Pakistan, and the GAINS model developed by the International Institute for Applied Systems Analysis (IIASA).

2.2.1. The EnerNEO Pakistan model

This study employs energy use pathways (sector-specific fuel-use data) generated by Enerdata for Pakistan with EnerNEO for future economic activity projections (EnerNEO Pakistan, 2018). EnerNEO is a partial equilibrium simulation model for the energy sector. The simulation technique employs dynamic year-by-year recursive modelling to generate complete development results for a variety of long-term time horizons.

Generic drivers that enter EnerNEO Pakistan model include macroeconomic variables such as GDP and population growth, as well as the intensity of future energy and climate policies, which are modelled using a carbon price signal and energy efficiency drivers. Sectoral drivers exist depending on the activity sector; for example, in the road transport sector, drivers include policy instruments such as biofuel blending policies, possible bans of ICE vehicles, sufficiency policies resulting in modal shifts and car-sharing behaviors, etc. The model uses national

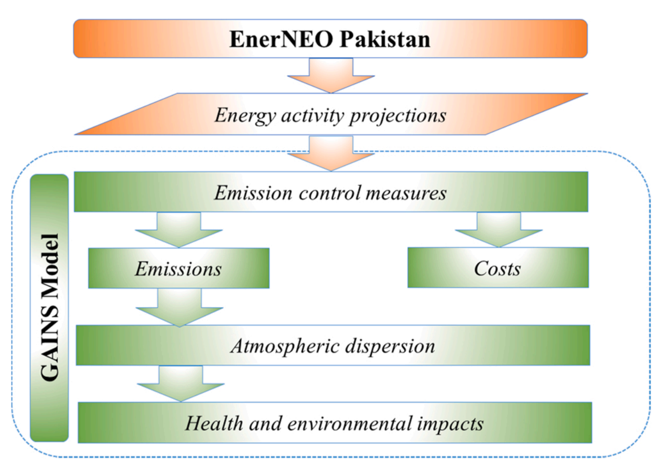

Fig. 1. The methodological approach: soft linking the EnerNEO Pakistan and GAINS models.

[1] See: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

[2] Enerdata developed the model with funding from the French Development Agency (AFD) and the German Corporation for International Cooperation (GIZ).

data, i.e., explicit historical data describing the observed energy context in Pakistan. These data are based on both recognized international sources (e.g., the International Energy Agency) and national statistics, and have been further refined in collaboration with the key government stakeholders (i.e., the Ministry of Energy and the Ministry of Climate Change).

The model provides projections for the energy sector (final energy demand of the country) up to 2050, broken down into individual subsectors, and of the power plants. It follows a top-down approach for modelling the demand, computing sectoral demands first, before allocating it by fuels using an econometric inter-fuel competition methodology. Consequently, the tool is able to calculate endogenously the final energy demand for each sector and fuel based on the consideration of activity, price, and energy efficiency effects. The energy demand of the transport sector is modelled with demand for each service determined as a function of per-capita GDP. On the supply side, the power sector is modelled using a detailed bottom-up approach. The tool includes an endogenous computation of investments in generating capacities and production dispatch, which impacts electricity prices in energy-consuming sectors. Finally, the user obtains values for capacity and production by fuel/technology, and utilization hours and levelized costs of electricity. The fossil fuel production and transformation sectors are modelled in a supply module, with the main inputs coming from the final demand and power sector modules. This enables EnerNEO to provide Pakistan with a complete energy balance for any given year up to 2050. Additional information about the model is provided in Section S.1 of the supplementary information (SI).

2.2.2. The GAINS model

The GAINS model provides a consistent framework for the analysis of co-benefits reduction strategies from air pollution and GHG sources (Klimont et al., 2017; Sanderson et al., 2013; Amann et al., 2011, 2008a). The model follows the pathways of the emissions from their sources to their impacts in the scenario analysis mode and provides estimates of costs and environmental benefits of alternative emission control strategies. In the optimization mode the model identifies cost-optimal allocations of emission reductions in order to achieve specified deposition levels, concentration targets, or GHG emissions ceilings (Wagner et al., 2012). The GAINS model was widely utilized to carry out policy evaluations in Europe (Amann et al., 2011), South Asia (Purohit et al., 2019, 2013, 2010; Bhanarkar et al., 2018; Karambelas et al., 2018; Amann et al., 2017; Mir et al., 2016; Dholakia et al., 2013;), East Asia (Liu et al., 2019; Klimont et al., 2009; Amann et al., 2008b), and at the global level (Amann et al., 2020).

The GAINS model represents Pakistan in four sub-regions (PUNJ, KARA, SIND, and NMWP). The megacity of Karachi (KARA) has been kept as one region, independent of the rest of Sindh (SIND) due to high economic activity in the city, large population, a huge number of industries located around the city, and heavy traffic load. Karachi contributes approximately 25–30% of Pakistan's GDP. Khyber Pakhtunkhwa and Balochistan (NMWP) are combined into a single region due to fewer economic activities and low population density. The province of Punjab (PUNJ) is treated as a separate region because it contributes roughly 55–60% of the national GDP. We used provincial statistical information to downscale and map national level data in GAINS regions of Pakistan.

For each of the source regions considered in GAINS, emission estimates for a particular emission control scenario consider (1) the detailed sectoral structure of the emission sources that emerges from the downscaling of the activity projection described above, (2) their technical features (e.g., fuel quality, plant types, etc.), and (3) applied emission controls (GAINS includes a database of over 1000 technical measures). The model then calculates resulting atmospheric $PM_{2.5}$ concentration fields for a specific range of current/future emissions. This estimation takes into account emissions within the particular region of interest and the inflow from the rest of Pakistan and neighboring countries. Premature deaths attributable to ambient $PM_{2.5}$ exposure are estimated by applying disease and age-specific attributable fractions to total disease-specific deaths. For calculating emission control costs, GAINS uses the international operating experience of pollution control equipment and extrapolates it to country-specific conditions. Additional information about the model is provided in the SI (Section S.2).

2.2.3. Emission scenarios

We examined the evolution of air quality under current legislation and the potential for further air quality improvements in this study. We analyzed three scenarios (see Table 1) for 2050 using 2015 as a base year, based on two energy scenarios and one end-of-pipe advanced emission control technology scenario. The first scenario is based on the current state of air quality regulations/standards/policies. While seeking additional air quality improvements, we conducted two additional scenarios: a) one with more stringent pollution standards in Pakistan, and b) one with sustainable development measures and advanced control measures applied concurrently. The three scenarios assume the same average annual GDP growth rate from 2015 to 2050 and illustrate the effects of various air quality and energy/climate policy measures.

2.2.4. Data sources

For macroeconomic development assumptions, this study uses the EnerNEO Pakistan model's medium-range economic growth rate forecasts (EnerNEO Pakistan, 2018), which anticipates 4.07% annual GDP growth between 2015 and 2050. Pakistan population forecasts (average annual of 1.56%) are based on the 2015 revision of the United Nations World Population Prospects (UNDESA, 2015), which includes country-level population projections up to 2100, and data for Pakistan until 2050 was used in EnerNEO Pakistan. Enerdata estimated Pakistan's GDP until 2050 using up-to-date data (as of 2018) from the French Center for Research and Expertise on the World Economy (CEPII), which is based on IMF projections. Fouré et al. (2013) discuss the CEPII approach and model for estimating GDP growth projections in better detail. The SI (Section S.3) contains a detailed description of EnerNEO Pakistan's key assumptions and data sources.

Using provincial statistical data from recent years in Pakistan, national-level projections of potential economic activities and macroeconomic drivers from EnerNEO Pakistan were downscaled and mapped

Table 1
Description of emission scenarios.

Emission scenarios	Description
1. BAU scenario	BAU is set up based on reference energy scenario of EnerNEO Pakistan model (EnerNEO Pakistan, 2018) assuming that the already implemented energy and climate policies (until the end of 2015) continue to be enforced (seeTable S4-S5). In addition, the BAU scenario considers existing policies and plans for end-of-pipe pollution control measures that will continue to be implemented during 2015–2050.
2. ACT scenario	ACT assumes full implementation of advanced air pollution control technologies (on BAU scenario) from 2025 onwards until 2050 (seeTable S6) which are already widely used in a number of industrialized countries (e.g., in the EU and Japan).
3. SDS	SDS adopts climate policy or 2 °C decarbonization scenario of EnerNEO Pakistan model (EnerNEO Pakistan, 2018) assuming lesser consumption of coal, oil, and gas, however, greater penetration of energy efficiency, renewables (hydro, solar, wind), and nuclear to compensate in the context of exploring response strategies to the 2 °C temperature increase limit by 2100 (see Table S7). In addition, SDS assumes implementation of advanced air pollution control technologies (as in ACT scenario) to deliver on the four main energy-related SDGs (SDG 3 – reducing health impacts due to air pollution, SDG 7 – achieving access to clean and modern energy, SDG 11 – reducing air pollution, and SDG 13 – combating climate change) simultaneously in a cost-effective and integrated way.

to GAINS region level structure (by sector, fuel, technology etc.) (APCMA, 2021; FAO, 2017; HDIP, 2015; IISD, 2016; MoF, 2018; MoPDR, 2010; NFDC, 2017; PBIT, 2018; PBS, 2020, 2015; Shahid et al., 2008). The GAINS database supplied activity data for industrial processes, agriculture, waste, and non-exhaust emissions from mobile sources.

3. Results

Using the soft-coupled EnerNEO Pakistan and GAINS models, we assess emissions of air pollutants/GHGs and air quality impacts in Pakistan for the base year 2015 (Section 3.1) and projections until 2050 (in five year intervals) under the BAU (Section 3.2), and alternative policy scenarios employing advanced technical measures and sustainable development measures (Section 3.3).

3.1. Understanding of the current situation

3.1.1. An emission inventory for 2015 – air pollutants and GHGs

The GAINS model starts with a 2015 emission inventory for the four disaggregated regions represented in the model for analyzing future air quality impacts (see Section 2.2.2).

As per regional activity statistics, Pakistan emitted approximately 806 kilotons (kt) of SO_2, 1037 kt of NO_x, and 1272 kt of primary $PM_{2.5}$ in 2015.[3] Punjab, Pakistan's most populous and industrialized province, emitted the highest $PM_{2.5}$ (58%) due to a significant number of households using solid fuels for cooking, NO_x (59%) due to high road vehicle density, and SO_2 (65%) due to a big number of thermal power plants installed capacity. Karachi, Pakistan's largest metropolis, has the second-highest share of SO_2 (14%) and NO_x (14%) emissions in the country (Fig. 2a). Mobile sources are estimated to account for 46% of NO_x emissions, followed by electricity production and industrial combustion (30%). The residential sector accounted for roughly half of $PM_{2.5}$ emissions, followed by industrial processes and combustion (35%) (Fig. 2b).

In 2015, Pakistan also emitted 171 megatons (Mt) of CO_2, 6425 kt of CH_4, and 141 kt of N_2O. Punjab contributes almost 48% of CO_2 emissions, 52% CH_4, and 67% N_2O to the national total, whereas NMWP contributes the second most CO_2 (19%) emissions (Fig. 2a). Electricity production and industrial combustion accounted for nearly 52% of total CO_2 emissions followed by transport (23%), residential/commercial (12%), and other (12%). Agriculture and waste (76% and 91%) produced the most CH_4 and N_2O emissions (Fig. 2b).

3.1.2. Air quality – ambient concentrations of $PM_{2.5}$

For the above-mentioned emission inventory, the GAINS model estimates air quality and its associated health impacts.

In 2015, Punjab, Sindh, and Karachi regions have the highest $PM_{2.5}$ concentrations (Fig. 3) due to high density of local polluting sources and heavily populated areas or large cities. Elsewhere in the country (NMWP region, particularly the country's south-western part), high concentrations (50–105 μg/m^3) may be attributed primarily to desert dust (because of the location of the Kharan Desert–a sandy and mountainous desert), transboundary air pollutants flows,[4] and, somewhat, sea salt. Therefore, $PM_{2.5}$ concentrations in the country's south-western part do not vary significantly across the scenarios analyzed in this study (Fig. 3).

Pollutants exhibit a north-south gradient (Fig. 3), which is probably influenced by emission distribution (largest in southern Pakistan) and air advection direction (prevailing westerly whole year long, with a northerly component in summer). Concentrations range from 80 to 105 μg/m^3 in Lahore city, 65–80 μg/m^3 in Faisalabad, and 35–65 μg/m^3 in Rawalpindi and Islamabad. This means that over 20 million people[5] in Punjab's four cities (including Federal city) are exposed to levels much beyond the NAAQS (15 μg/m^3) and WHO recommended limit (5 μg/m^3). In the rest of Punjab (about 90 million people), concentrations range from 25 to 65 μg/m^3. Karachi (population 16 million) has the worst air quality with concentrations above 105 μg/m^3. Concentrations in Federally Administered Tribal Areas (FATA) with 5 million residents range from 10 to 25 μg/m^3. More effort is required to bring all southern regions into compliance with the NAAQS, while northern regions must ensure that their potential economic development does not jeopardize air quality. A comparison of modelled $PM_{2.5}$ concentrations with observed concentrations is shown in the SI (Section S.2.1). Although there is considerable scatter, the model appears to reflect observed concentrations reasonably well.

3.1.3. Air quality impacts – health impacts

To assess the health impacts, GAINS calculates the number of premature deaths attributable to outdoor $PM_{2.5}$ exposures. Outside of Europe, GAINS uses the approach of Global Burden of Disease studies to calculate mortality by using country-specific data on ambient $PM_{2.5}$ concentrations at relevant resolution (urban background), population data on the same spatial distribution, exposure-response relationships, and baseline mortality data (by disease and age). The total number of premature deaths in Pakistan in 2015 was estimated to be 81565 (Fig. S5a), which falls within the upper and lower bounds (69700 – 144500: mean 104400) of HEI (2020). This estimate, however, is slightly lower than Cohen et al. (2017) (114300–159200: mean 135100). The main difference appears to be a lower natural dust contribution to the GAINS model (as determined by the EMEP-CTM), a very uncertain feature of atmospheric modelling. Punjab has the highest proportion of premature mortalities (58%) followed by NMWP (18%), Sindh (15%), and Karachi (9%).

3.2. The baseline projection up to 2050

3.2.1. Macro-economic development and energy consumption

The economic and population growth baseline projections are based on the results of EnerNEO Pakistan (2018), adopted by the Government of Pakistan. It forecasts annual population growth of 2.02% in Pakistan until 2030 and 1.22% afterward, resulting in a 72% larger population in 2050 than in 2015 (Fig. 4a). Concurrently, GDP per capita would increase by about 2% per year, resulting in an almost fourfold increase in total GDP by 2050 (Table S3).

The model was also used to generate the corresponding energy use pathways (Section 2.2.1). These represent Pakistan's current and prospective energy and climate policies, including increased coal use in power plants, renewable energy targets, and the drive to deliver affordable electricity. Consequently, primary energy demand would increase by a factor of three between 2015 and 2050, with a general shift toward coal. Biomass use is unlikely to change significantly because it is a low-cost source of energy for rural households. Coal consumption would increase by a factor of 18 followed by renewables (wind, solar, hydropower) by a factor of 6, and nuclear (by a factor of 5). The use of oil and gas would increase by 1.9 and 2.6 times respectively (Fig. 4b). The high increase in coal's share of primary energy supply is in the sense of a BAU scenario, a continuation of trends observed in recent years, a sort of counterfactual scenario. The primary objective of such a scenario is to use it as a benchmark point for analyzing the other energy scenarios such as the sustainable development scenario. Therefore, despite the fast-changing international policy context surrounding fossil fuels in

[3] See: GAINS scenario <PAKI_BAU_CPS_2021 > available at: https://gains.iiasa.ac.at/gains4/INN/index.login?logout= 1&switch_version=v0

[4] FAO (2018) indicates 65% of aerosol sources within Pakistan and 35% in neighboring countries (India, Afghanistan, and Iran).

[5] National/provincial/city level demographic statistics are available at: https://www.macrotrends.net/; https://population.un.org/wpp/; and https://www.finance.gov.pk/survey_1718.html.

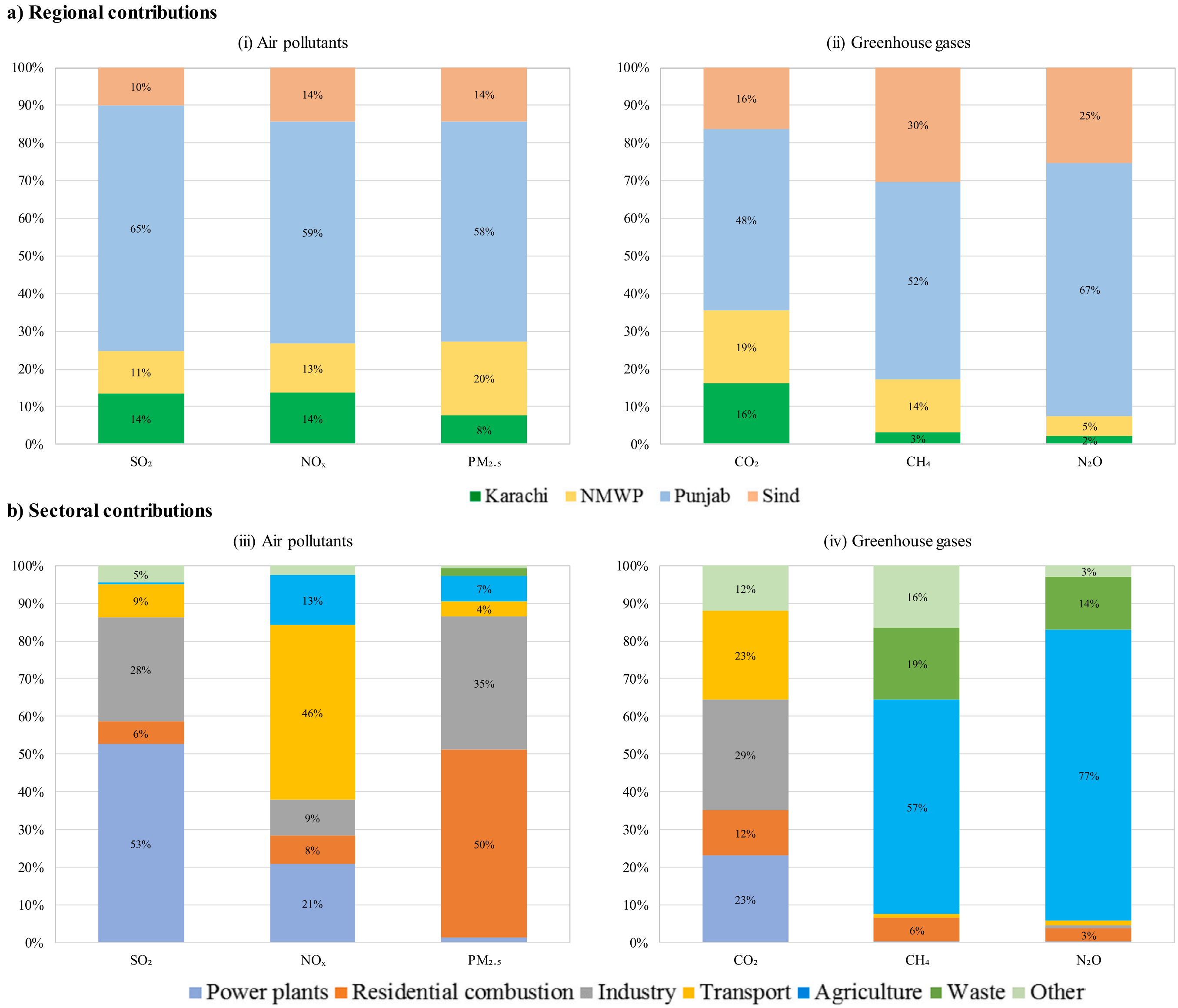

Fig. 2. Air pollutants and GHG emissions in Pakistan for 2015 a) regional contributions and b) sectoral contributions.

general, and coal in particular, coal continues to have a relatively high share of Pakistan's primary energy supply.

3.2.2. *Baseline projections for air pollution and GHG emissions*

The BAU scenario is developed as a reference case to evaluate the efficacy of additional policy interventions. It examines the future evolution of air pollution and GHG emissions with their effects, assuming existing energy and climate policies (until 2015) continue to be enforced (see Table S4). Additionally, the scenario considers existing and planned air pollution control policies (see Table S5). The baseline projection contains no assessments of the effects of implementation failures because it is assumed that these initiatives would be implemented successfully.

Fig. 5a shows the baseline projection of sectoral air pollutant emissions in Pakistan. Power plants and industrial combustion would continue to dominate SO_2 emissions, which would increase by a factor of 3 between 2015 and 2050. NO_x emissions would be dominated by transport and power plants, followed by industry and agriculture. NO_x emissions would double, while $PM_{2.5}$ emissions would increase by a factor of 2.6 between 2015 and 2050 (Fig. 5a). While residential combustion accounted for almost half of Pakistan's $PM_{2.5}$ emissions in 2015, that share would drop to less than half by 2050, owing to a large increase in coal-fired power plants emissions. Power plants would account for over 47% of $PM_{2.5}$ emissions in 2050, followed by industry (22%), residential (22%), transport (3.2%), agriculture (3.1%), waste (1.1%), and others (1.4%).

Aside from air pollution, lack of effective mitigation efforts would result in a considerable increase in GHG emissions. Fig. 5b shows Pakistan's sectoral baseline GHG emission projections. Note that the CO_2 emissions are presented in Mt whereas CH_4 and N_2O emissions are presented in kt. CO_2 emissions would increase fourfold due to the expected increase in economic activity. CH_4 and N_2O emissions are expected to increase 51% and 66% respectively. Fig. 5c presents the total GHG emissions (in CO_2 equivalent) using IPCC (2013) Global Warming Potentials for CH_4 ($GWP_{100} = 28$) and N_2O ($GWP_{100} = 265$). Accordingly, Pakistan's total GHG emissions would increase by a factor of 2.5 between 2015 and 2050 (Fig. 5c).

3.2.3. *Baseline projections for air quality and health impacts*

Fig. S6 shows a comparison of $PM_{2.5}$ concentrations in 2030 and 2050 under the BAU scenario. In large parts of Pakistan, $PM_{2.5}$ concentrations would range from 50 to 80 $\mu g/m^3$ in 2030–65 to 105 $\mu g/m^3$

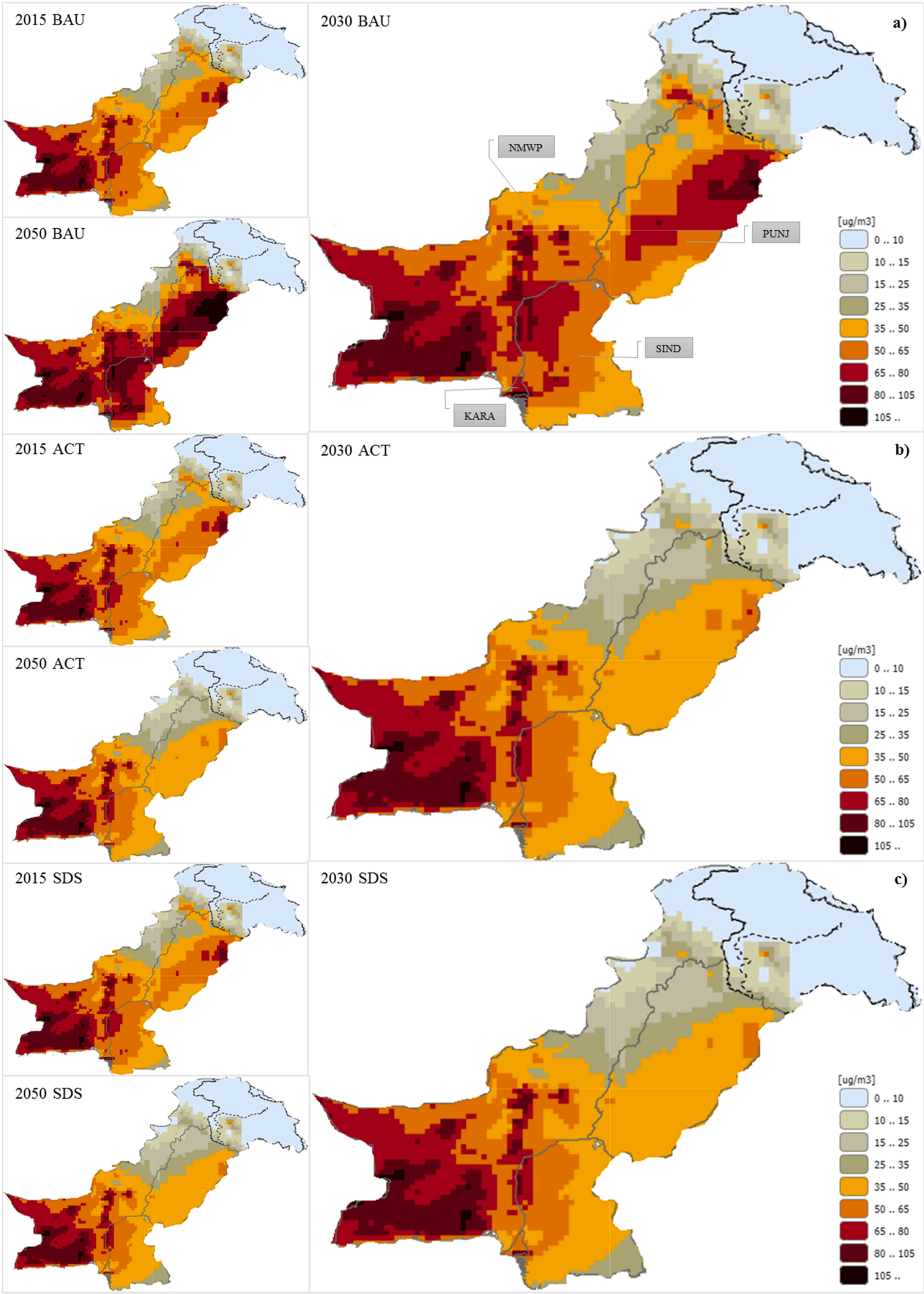

Fig. 3. Ambient concentrations of $PM_{2.5}$, in a) 2015 and for the business as usual (BAU) scenario in 2030 and 2050; b) 2015 and for the advanced control technology (ACT) scenario in 2030 and 2050; and c) 2015 and for the sustainable development scenario (SDS) in 2030 and 2050.

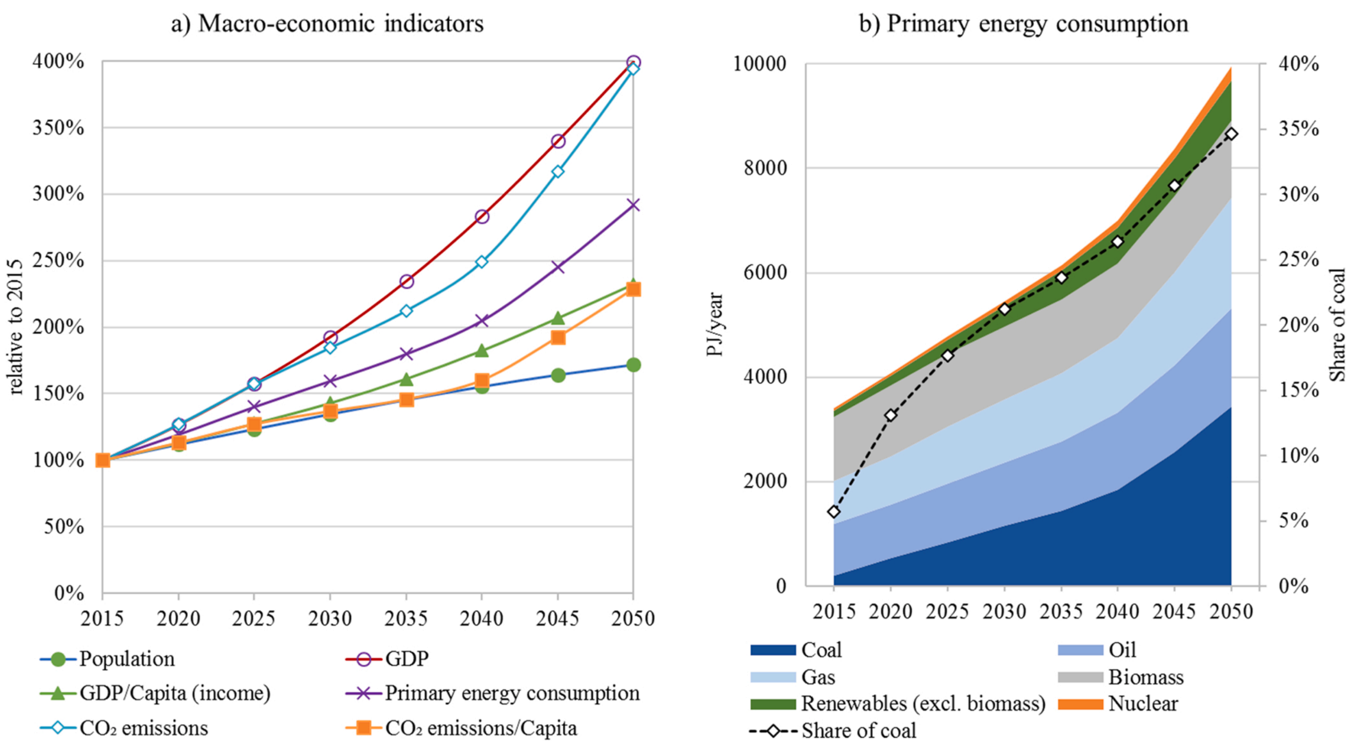

Fig. 4. Assumed baseline trends, of a) macroeconomic indicators relative to the year 2015 and b) primary energy consumption in PJ per year.

in 2050, with some areas exceeding 105 μg/m^3 (Fig. 3a). Such high concentrations would undoubtedly have a significant impact on public health. Fig. S5a shows the BAU estimates of premature deaths and $PM_{2.5}$ concentrations (displayed in Fig. 3a). Premature deaths are expected to increase in Pakistan from 81565 in 2015–117241 in 2030 and 208236 in 2050. Fig. S5b shows a strong positive correlation between $PM_{2.5}$ concentrations and $PM_{2.5}$-related premature deaths. Although assessing the climatic impacts of increased GHG emissions (Fig. 5b) is beyond the scope of this study, the magnitude would be significant on a global scale.

3.3. Alternative policy scenarios

3.3.1. Air pollution reductions through advanced technical measures

Considering Pakistan's projected economic growth, the current emission control measures would be insufficient to reduce air pollution. The likely benefits of advanced end-of-pipe technologies, successfully implemented in many developed countries, are explored in an illustrative 'advanced control technology (ACT)' scenario. This scenario assumes stringent SO_2, NO_x, and $PM_{2.5}$ emission limits for large point sources compared to the BAU scenario (see Table S6). The ACT scenario assumes the application of end-of-pipe technologies to all relevant pollution sources in Pakistan from 2025 onwards. However, this scenario is limited to pollution control equipment and excludes other economic structural changes like energy efficiency, process improvements and clean technologies adoption.

Implementing advanced end-of-pipe measures could significantly reduce baseline emissions in Pakistan (Fig. 6a). In the ACT scenario, SO_2, NO_x, and $PM_{2.5}$ emissions could be reduced by 39%, 50%, and 31% in 2030, and 29%, 35%, and 56% in 2050, respectively, compared to 2015. $PM_{2.5}$ concentrations would decrease from 75 μg/m^3 and 93 μg/m^3 in the baseline scenario to 51 μg/m^3 and 47 μg/m^3 in the ACT scenario in 2030 and 2050, respectively. (Fig. S6). Consequently, cleaner air would reduce $PM_{2.5}$-related mortalities from 208236 in the baseline scenario to 162015 by 2050, and from 117241 to 101378 by 2030 (Fig. S6). Therefore, advanced emission control measures on large sources would substantially cut future emissions, resulting in better air quality (Fig. 3b) and reduced health impacts in Pakistan.

3.3.2. Air pollution reductions through sustainable development measures

An illustrative 'sustainable development scenario (SDS)' explores the additional air quality benefits from such policy initiatives targeted at a broader development context (Table S7). It considers a significant transformation of Pakistan's energy system, demonstrating how the country may pivot to achieve the four major energy-related sustainable development goals (SDGs) – SDG 3, SDG 7, SDG 11, and SDG 13 – as categorized and prioritized in the national SDG framework (MoPDR, 2018, 2019; UN, 2015). Winkler et al. (2008) identified four ways to quantify the effect of sustainable development policies and measures on development and emissions. These include case studies, national energy modelling, analysis of sectoral data, and inclusion of policies in global emission allocation models. We used a national energy model to investigate the local sustainable development and climate implications of energy policies, as this method is most useful in countries like Pakistan, where GHG emissions are primarily driven by the energy sector.

Accordingly, the SDS adopts an energy sector decarbonization scenario developed by Enerdata using the EnerNEO Pakistan model (EnerNEO Pakistan, 2018) in the context of exploring response strategies to the 2 °C temperature increase limit by 2100 (SDG 13). Assumptions include large-scale use of renewables (hydro, wind, solar), nuclear, and energy efficiency measures (SDG 7), plus advanced technical measures used in the ACT scenario (part of SDG 3 and SDG 11) to support the country's transition to less energy-intensive industries. Thereby, it forecasts 92% less coal, 28% less oil, and 58% less gas consumption compared to the baseline case for 2050. Similarly, nuclear would expand by 3.2 times, while renewable contributions would be more than double as compared to the BAU scenario in 2050 (Fig. S7). The underlying population growth and economic development projections are the same as in the baseline forecast.

Sustainable development measures combined with advanced technical measures would result in significant emission reductions. Fig. 6a presents SO_2, NO_x, and $PM_{2.5}$ emissions in 2015, 2030 and 2050 under the BAU and alternative scenarios. In 2050, under SDS, SO_2, NO_x and

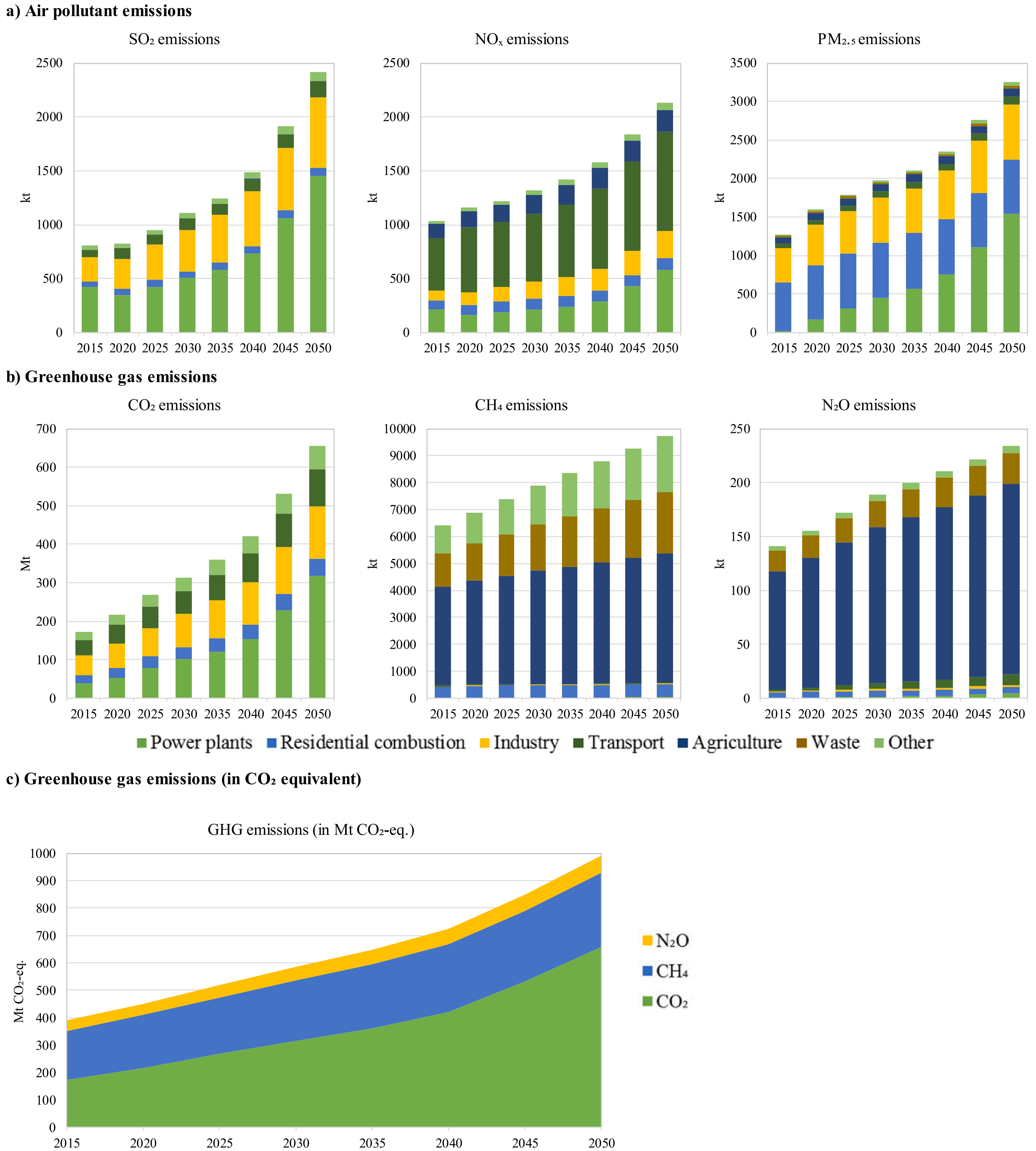

Fig. 5. Baseline projection of a) air pollutant and b) GHG emissions by sector and c) CO_2 equivalent emissions by GHG in Pakistan from 2015 to 2050.

$PM_{2.5}$ emissions would decrease by 64%, 56%, and 56% in 2050 compared to 2015. Lower emissions would result in lower health impacts due to lower levels of $PM_{2.5}$ in the ambient air (Fig. 3 and Fig. S6), supporting to achieve SDG indicators 3.9.1 (mortality rate attributed to household and ambient air pollution) and 11.6.2 (population-weighted annual mean levels of $PM_{2.5}$ in cities), respectively. $PM_{2.5}$ concentrations would drop to 45 μg/m^3 by 2050, compared to 93 μg/m^3 (a 51% reduction) in the baseline projection. Similarly, mortalities fall by 24% to 159163 in 2050, compared to 208236 in the baseline estimate. Furthermore, such a strategy would result in 64% lower CO_2 emissions in 2050 than the baseline case (Fig. 6b).

4. Discussions

4.1. Emission control costs

The GAINS model calculates unit costs for emission reductions over the (technical) lifetime of control equipment from the perspective of a

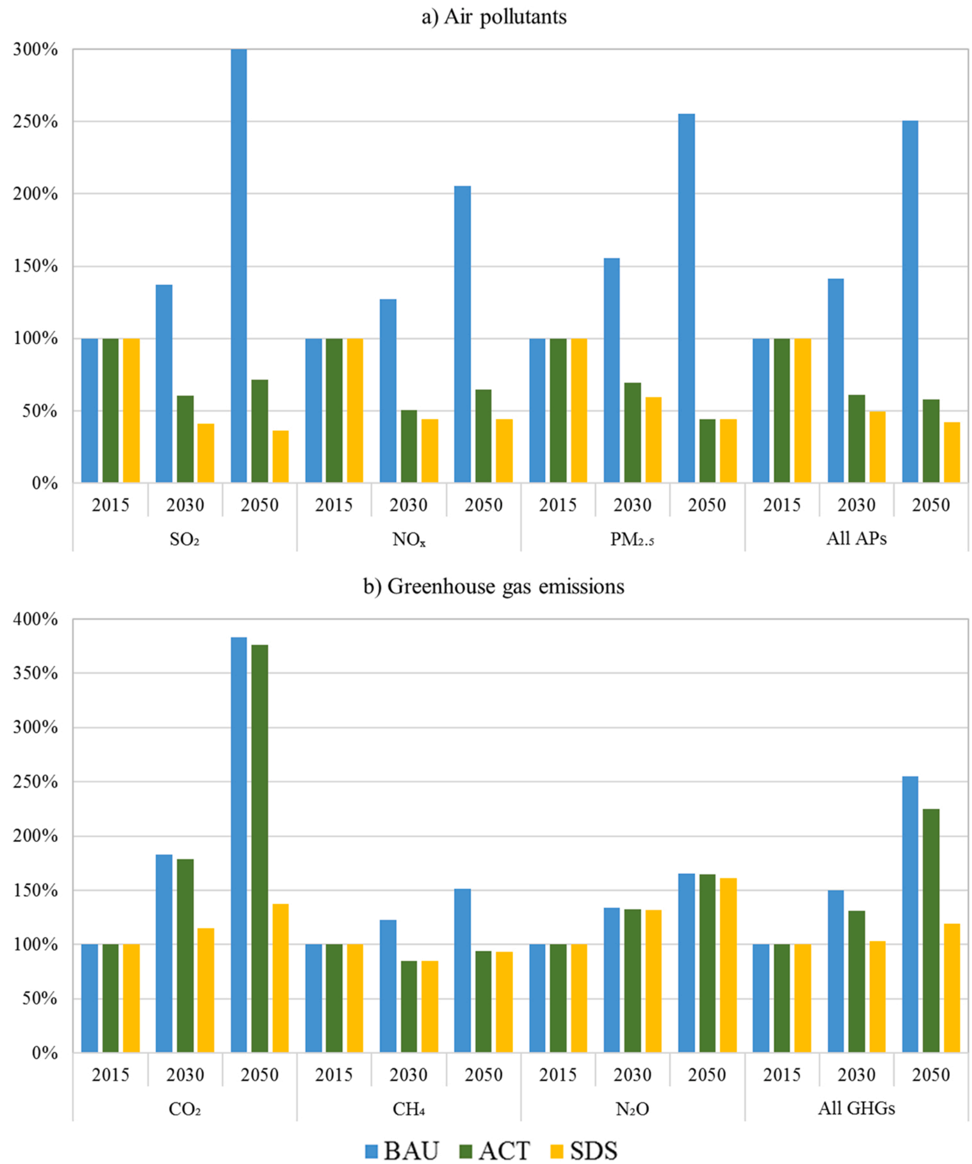

Fig. 6. Emissions of a) air pollutant and b) GHG in Pakistan for the emission control scenarios.

social planner (standard discount rate of 4% per year), focusing on the diversion of societal resources. This approach excludes transfer payments such as taxes, subsidies and profits, and balances up-front investments with subsequent cost savings, for example from lower energy consumption (Wagner et al., 2012). The model considers international cost data for technologies and adjusts them to country-specific conditions, considering local labor costs, energy prices, costs of by-products, etc. to estimate costs for applying technology in a given country. This strategy, however, does not include feedback on the economy. All costs are expressed in (economic) real terms (2015) and remain constant over time. Furthermore, the model estimates the scope for additional environmental improvements provided by commercially available emission control technologies (excluding the potential from structural changes), their costs, and the composition of cost-effective portfolios of measures that achieve higher environmental protection at the lowest possible cost. One limitation of the analytical approach used in this study is that mainly end-of-pipe emission control measures are included in the analysis. However, focusing on this type of measure is consistent with the current effort on best available emission control technologies in existing air pollution control policies in industrialized countries, and the existing policy distinction between climate and air pollution challenges. This distinction is, however, known to reduce the cost-effectiveness of policies and limits the policy push for using climate measures to help reach air pollution objectives and vice versa.

With this context in mind, the GAINS model computes the costs of emission reduction initiatives introduced in 2015 at €0.26 billion or 0.12% of the GDP of Pakistan. These control costs were associated with air pollutant (SO_2, NO_x, and $PM_{2.5}$) emissions from power plants, industry, mobile sources, residential, and other (fuel conversion/production/distribution and non-road machinery) sectors. Approximately, 84% of total costs are attributable to mobile sources (i.e., for the country's Pak-II emission standards) followed by residential (12%), industry (3%) and power plants (1%). In 2050 (BAU scenario), implementing current pollution control regulations would cost €1.5 billion, or 0.17% of GDP, with mobile sources accounting for the lion's share of emission control costs (Fig. 7). Nevertheless, widespread adoption of advanced technology (ACT scenario) entails certain costs. By 2030, air pollution control costs would reach €6.5 billion (1.6% of GDP), and nearly €12 billion (1.4% of the GDP) by 2050. Although this is significantly higher than the base year costs (€0.26 billion), it is worth noting that the underlying economic forecast for 2050 expects a fourfold increase in GDP (Fig. 7). Notably, the SDS incorporates policies aimed at reducing fossil fuel use,

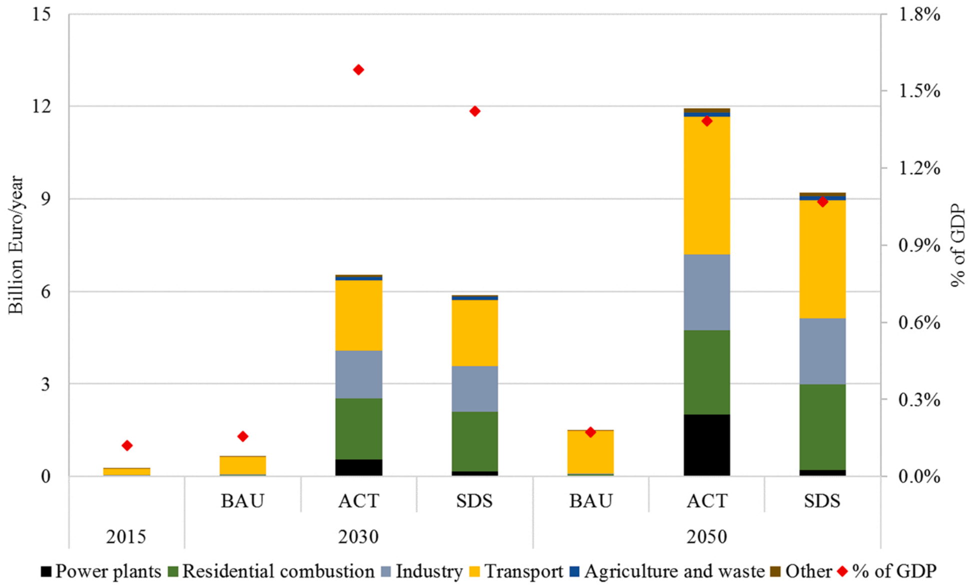

Fig. 7. Air pollutant emission control costs for the various scenarios.

resulting in lower pollution control costs than the ACT scenario. This occurs as a side benefit of presumed energy policies, rather than as a result of stringent air pollution controls. In 2050, such an alternative energy policy would save costs by €2.7 billion (0.32% of GDP) (Fig. 7). These savings are a result of decreased coal and oil use, which accordingly involve less air pollution control-related installations.

Mitigation costs represent a significant share of GDP in the SDS and ACT scenario. This is because, in a constrained, low-emission scenario like the SDS, not only energy efficiency but also sufficiency efforts (driving less, producing less, for example) should be observed before 2050, implying that economic growth may be more moderate than initially assumed in the scenario. Nevertheless, EnerNEO remains an energy model rather than a macro-economic model capable of capturing such effects on its own. Even with a higher reduction in air pollution levels, the SDS has lower air pollution control costs as compared to the ACT scenario. While the inclusion of structural measures in the SDS portfolio allows further reductions of primary $PM_{2.5}$ beyond what end-of-pipe measures alone could deliver, the model excludes the cost of structural changes. Adding them up, however, may affect the picture depicted in Fig. 7, which shows that air pollution control is less expensive in the SDS than in the ACT scenario.

4.2. Implications for SDGs

The Government of Pakistan has worked to integrate the SDGs into all its policies, plans, and strategies since the SDGs were adopted (UN, 2015). The SDGs are reflected in Pakistan's long-term development agenda, provincial development strategies, and five-year plans. All levels of government (i.e., federal, provincial, local) are actively involved in implementing the SDGs. The federal government has created a comprehensive national SDG framework to identify and prioritize goals in various areas and to guide the design of development strategies (MoPDR, 2018a, 2018b). The national and provincial assemblies have formed task forces to track progress toward the SDGs, and the government conducted a voluntary national review in 2019 (MoPDR, 2019) to assess its progress. Although Pakistan has made reasonable progress in some areas, it needs to redouble its efforts to meet the SDGs. For example, in one of the critical sectors – the electricity sector, achieving a more sustainable power mix would necessitate annual spending of 0.7% of GDP from 2020 to 2030, along with a planned shift toward renewable energy, which could result in significant environmental benefits on a local and global scale (Brollo et al., 2021).

Compared to the ACT scenario (not changing activity levels), the SDS considers sustainable development policies and measures that promote reducing and substituting major polluting activities with cleaner alternatives/technologies, such as: replacing coal with gas and renewables in power/industry; using clean cookstoves; and improving energy efficiency and public transport. Thereby, successful implementation of the sustainable development scenario inclines reduction in air pollution at a lower cost, resulting in more GHG emission reductions and reinforcing Pakistan's achievement of energy-related SDGs (SDG 3, SDG 7, SDG 11, and SDG 13).

Consequently, under the SDS, Pakistan's CO_2, CH_4, and N_2O emissions would be 64%, 39%, and 3% lower in 2050 compared to the BAU scenario. Total GHG emissions (in CO_2 equivalents) would drop by 32% in 2030 and 53% in 2050 (Fig. 6), reinforcing the implementation of the following SDG indicators: 13.2.1 (low GHG emissions development); 7.1.1 (access to modern electricity); 7.1.2 (access to clean fuels/technologies for cooking); 7.2.1 (increase in the share of renewable energy); and 7.3.1 (energy efficiency improvement). This also supports Pakistan's updated NDCs target of a 50% reduction (15% unconditional and 35% conditional) in GHG emissions by 2030. Likewise, lower air pollutant emissions will help to achieve SDG indicators 3.9.1 (reduce the mortality rate from air pollution) and 11.6.2 (reduce urban air pollution). Additional benefits to other SDGs (Dagnachew et al., 2021; Longhurst et al., 2018) include: water availability improves from lower coal consumption (SDG 6); grid expansion – infrastructure development (SDG 9); new jobs in clean technologies manufacturing (SDG8); increased renewable energy use reduces natural resource depletion (SDG 12); lower energy bills increase disposable income (SDG 10); better transport infrastructure (SDG8); and public-private partnerships to share knowledge and experience (SDG 17).

5. Uncertainties and limitations

GAINS model emission estimates generally compare well to those available from national/international sources (see Table S1, S2). However, there may be significant uncertainties for pollutants (such as $PM_{2.5}$, SO_2, and NO_x) for which little information is available for Pakistan's conditions. The model used emission factors from countries with similar conditions to arrive at an initial estimate. The actual magnitude of pollutant emissions from various sources might differ. Owing to the GAINS model's widespread use over the last three decades, it provides procedures and emission data for a variety of sources. Even though they apply to a wide range of situations, they do not generally apply to all of Pakistan's major pollution sources. Therefore, further work is needed in order to verify and improve local/regional parameters and emission factors.

A comparison of modelled $PM_{2.5}$ concentrations to measurements made in different studies (Alam et al., 2015; Aslam et al., 2020; Cohen et al., 2017; IQAir, 2021; Khanum et al., 2017; Mehmood et al., 2018; Niaz et al., 2016; Rasheed et al., 2015; Shahid et al., 2016; WHO, 2021) is shown in Fig. S4 (see Section S.2.1). Despite some scatter, the model appears to replicate observed concentrations well in general. The small number of points, and their quantized distribution in the graph, suggest that $PM_{2.5}$ measurements suitable for validation are limited. Pakistan has very few public air quality monitors, and it is unclear whether data from the monitoring network will be made public in real-time. Most of the data in Pakistan comes from low-cost sensors operated by dedicated individuals and non-governmental organizations like Pakistan Air Quality Initiative. To better identify pollution sources and encourage action, a nationwide monitoring network with enhanced data granularity and coverage in more cities is critically important (IQAir, 2021).

Source attribution/apportionment to quantify the contributions of different sources, sectors and regions to ambient $PM_{2.5}$ concentrations is not done in this study. Further research is required to determine the proportion of health impacts (from outdoor $PM_{2.5}$ exposures) attributable to particle emissions from household solid fuel combustion. Aside from outdoor health impacts, severe health risks from exposure to indoor particle emissions are a matter of concern and must therefore be estimated.

Uncertainties exist in the macro-economic development and energy consumption quantitative forecasts, which could lead to different outcomes than those presented in this study. One of the most important factors affecting long-term stability and the most difficult to forecast reliably is the future GDP growth rate. The current Covid-19 crisis, and its impact on short-term GDP in particular, were not considered in this study. Other significant uncertainties in EnerNEO assumptions include fossil fuel price long-term evolutions and energy efficiency improvements assumed in the sustainable development scenario. The study also only assesses co-benefits (positive effects) of air pollution and GHG mitigation; and not trade-offs (negative side effects) with development objectives.

In general, the GAINS model focuses on add-on technical solutions (measures with a direct impact on the emission factors). Structural changes can be simulated by introducing changes in the baseline activity levels (i.e., the energy scenario input data). Structural measures will have larger (synergetic) reduction potentials than simple add-on controls addressing one pollutant by reducing emissions of different air pollutants (as well as GHGs) simultaneously. Therefore, a rigorous cost-benefit analysis (quantifying or monetizing co-benefits to describe the total value of different co-benefits) of these policy options must be carried out.

6. Conclusions

This study analyzes co-benefits of air pollution control and climate change mitigation strategies in Pakistan under the BAU and alternative scenarios. Our results reveal that Pakistan's current air pollution control measures are insufficient to meet the country's air quality standards under the BAU scenario. We find that trends in air pollution can be reversed with advanced control technology and sustainable development scenarios, particularly in the SDS, with lower costs and higher reductions in GHG emissions as compared to the BAU and ACT scenarios. In the BAU scenario, ambient $PM_{2.5}$ concentrations in Pakistan would increase by a factor of 1.5 by 2050, resulting in more than double the number of premature deaths. However, embedding advanced control technologies within sustainable development policies scenario would reduce 76–88% of SO_2, NO_x, and $PM_{2.5}$ emissions in 2050 as compared to the BAU. The SDS scenario will halve $PM_{2.5}$ concentrations by 2050 that could avoid 24% of total $PM_{2.5}$ attributable deaths. In addition, the cost of air pollution control would also decrease by 23% (0.32% of GDP) by 2050 in the SDS scenario as compared to the ACT scenario. Furthermore, sustainable development interventions facilitate the achievement of multiple SDGs, most notably SDG 13 on climate action, by reducing total GHG emissions (in CO_2 equivalent) i.e., a 53% reduction compared to the BAU by 2050. However, it should be noted that the costs of GHG reduction are not estimated in this study, which, if included, may affect the overall cost.

The study addresses a policy-relevant issue on two counts. First, air pollution is a major public health problem in Pakistan. Second, tackling climate change is a major issue for all countries in the world. The final takeaway is that it shows how climate mitigation can be a side benefits of air pollution control, whereas the climate change literature typically tends to consider air pollution reduction a co-benefit of mitigation. This is policy-relevant because allowing scarce resources to local air pollution control might be easier to achieve politically. Consolidating law enforcement and economic stimulus would be a critical component of Pakistan's progress toward improved air quality and climate change mitigation, which is beyond the scope of a scientific analysis. Therefore, the scenarios presented here demonstrate the effectiveness of an integrated approach to pollution control over a conventional approach, which could result in significant cost savings.

CRediT authorship contribution statement

Kaleem Anwar Mir: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Pallav Purohit:** Conceptualization, Methodology, Software, Data curation, Writing – review & editing, Visualization. **Sylvain Cail:** Software, Data curation, Writing – review & editing. **Seungdo Kim:** Funding acquisition, Supervision, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.03.008.

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