NATIONAL ASSESSMENT OF THE COSTS OF INACTION OF TACKLING AIR POLLUTION IN INDONESIA

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ACRONYMS

AHRQ	Agency for Healthcare Research and Quality
ASEAN	Association of Southeast Asian Nations
BC	Black Carbon
CH_4	Methane
CO_2	Carbon Dioxide
CRFs	Concentration-response Functions
EANET	Acid Deposition Monitoring Network in East Asia
GAINS	Greenhouse Gas – Air Pollution Interactions and Synergies Model
GBD	Global Burden of Disease
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
LPG	Liquefied Petroleum Gas
NDC	Nationally Determined Contribution
NH_3	Ammonia
NMVOC	Non-methane Volatile Organic Compound
NO_x	Nitrogen Oxides
NO_2	Nitrogen Dioxide
NPS	New Policy Scenario
O_3	Ozone
OC	Organic Carbon
OECD	Organization for Economic Co-operation and Development
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SDGs	Sustainable Development Goals
SDS	Sustainable Development Scenario
SLCPs	Short Lived Climate Pollutants
SO_2	Sulfur Dioxide
UN	United Nations
UNEP	United Nations Environment Programme
UNEP/CCAC	United Nations Environment Programme/Climate and Clean Air Coalition
VOLY	Value of a Life Year
VSL	Value of a Statistical Life
WHO	World Health Organization
YLLs	Years of Life Lost

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EXECUTIVE SUMMARY

This assessment provides a preliminary quantification of the costs of not taking further action on air pollution in Indonesia. It quantifies and compares the potential health costs that come under a scenario in which no further measures beyond current policy are taken, with future scenario in which 12 solutions (bundles of measures) are introduced. In addition to looking at health impacts, the assessment also highlights co-benefits for climate change that would also be missed if further measures are not implemented. The key findings of this initial assessment are:

Indonesia has introduced effective policies which have improved air quality over the last decade but more needs to be done. Despite recent progress, air pollution remains a significant problem in Indonesia. Even considering current air quality legislation, the health burden from air pollution exposure is projected to increase, due to economic and population growth as well as population aging. This assessment calculates that without any additional action on air pollution, there will be over 216 thousand premature deaths due to ambient air pollution exposure in Indonesia per year by 2030.

Further action could have significant health benefits for the population of Indonesia. Implementing further policies beyond current legislation could avoid over 132 thousand premature deaths, 32 thousand hospital admissions and 18 thousand emergency room visits due to poor air quality every year by 2030 in Indonesia.

The human health related costs of not taking further action on air pollution are estimated to be equal to about 1.6% of Indonesia's Gross Domestic Product (GDP) in 2030. Lack of immediate further action on air pollution could cost Indonesia 27 billion USD a year in 2030, based on a selection of mortality and morbidity impacts of air pollution. This equals about 1.6% of Indonesia's GDP for 2030. The actual cost of inaction will likely be higher if all other costs and foregone benefits are accounted for.

There are proven measures to improve air quality and achieve large health benefits in the near term. 12 key solutions were identified which could deliver significant air quality benefits. Of these 12 solutions, the policies which could lead to the largest benefits in Indonesia include policies relating to accelerated introduction of electric vehicles and strengthened emission standards for road transport, increased renewable electricity generation capacity, enhanced emission standards for industry and improved. These measures alone would capture about 75% of the mitigation potential in terms of exposure and monetized benefits.

The proposed 12 solutions also result in significant reduction of GHG emissions and could also have multiple other benefits. This assessment shows that implementing the 12 solutions for clean air would also have benefits for reducing GHG emissions with benefits for climate change and could help Indonesia achieve its climate targets. If implemented, the solutions could also deliver multiple other co-benefits, supporting the achievement of other development priorities related to several Sustainable Development Goals. Therefore, the cost of inaction is likely to be even higher than the figure estimated in this assessment.

Quantifying the costs of inaction of tackling air pollution provides useful evidence which can be used to promote action. Through quantifying the high costs of not acting on air pollution, the results of this assessment can be used to motivate action. The initial results presented here can be used to support Indonesian policymakers and decisions-makers in the design and implementation of new policies and measures and facilitate cross-governmental dialogues on effective air quality management.

1. Introduction

1.1. Background

Air pollution poses a substantial threat to the health and well-being of the 660 million people living in the Association of Southeast Asian Nations (ASEAN) region. Indonesia is not exempt from this burden; exposure to fine particulate matter ($PM_{2.5}$) was estimated to cause about 107,000 (77,000-138,000) premature deaths annually in Indonesia in 2019 (Murray et al., 2020). Furthermore, exposure to $PM_{2.5}$ is responsible for a high burden of morbidity from cardiovascular and respiratory diseases, while air pollution also affects ecosystems through deposition of nitrogen and sulfur, leading to acidification, eutrophication, and loss of biodiversity.

Indonesia, the world's fourth most populous country, has an estimated population of over 276 million people, 57% of whom live in urban areas. Within its long-term national development strategy, Indonesia has set out a route to be a fully developed economy by 2045, aiming for at least a 5% increase in GDP per year. Without significant action, this economic growth, combined with expected increases in population and urbanisation could lead to negative environmental impacts including worsening air quality. There are well known measures which, if effectively implemented, could successfully reduce air pollution and its associated impacts, and increasing efforts have been taken in recent years to counteract the air pollution problem in ASEAN countries. Indonesia has recognised the need to take decisive action on mitigating air pollution and in 2020 published its first strategic plan for air pollution control (2020-2024), while there are several other sector specific initiatives such as implementing emission standards for vehicles and emission standards and regulations for industry which may have had some success in the small reduction in population weighted average $PM_{2.5}$ exposure over the past 20 years (State of Global Air, 2020). However, even if current policies and legislation are effectively implemented, it is likely that continued population growth, urbanization and economic growth will largely offset the achieved reductions and lead to further worsening of air quality in the region with negative impacts for health (United Nations Environment Programme/ Climate and Clean Air Coalition [UNEP/CCAC], 2023). To limit the multiple negative impacts of air pollution it is therefore important to consider what additional actions could be effective and to not only explore the implications of current policies, but also opportunities for further mitigation.

Tackling air pollution can also have largely positive benefits for mitigating climate change. Some pollutants, known as short lived climate pollutants (SLCPs), contribute directly to both climate change and air pollution, while air pollutants and long-lived greenhouse gases (GHGs) often come from the same source. Consequently, taking an integrated approach to air pollution and climate change could result in multiple benefits for health and the environment (Haines et al., 2017) and achieve other Sustainable Development Goals (SDGs). The UNEP/CCAC Assessment on Air Pollution in Asia and the Pacific (United Nations Environment Programme [UNEP], 2019) and the Clean Air and Climate Solutions for ASEAN Report (UNEP/CCAC, 2023) took this perspective and identified a portfolio of solutions that could be implemented with benefits for air quality and climate as well as other development priorities. This assessment builds on the previous analysis and utilizes some specific solutions highlighted in the report (see Box 1).

Mitigation measures to tackle air pollution are often associated with an economic burden that would not only be imposed on polluting industries but also impact a wide range of stakeholders from individual citizens to businesses and local government. Hence, costs are sometimes mentioned as arguments against stricter legislation. However, the impacts of air pollution also impose costs to society resulting in economic losses, for example costs to the health care system due to increased levels of attributable disease or economic losses due to a reduced work force through death and illness. Therefore, not acting on air pollution is also costly, and quantifying these costs of inaction, as a counterbalance to the costs of action (i.e., of implementing new mitigation measures), can be an important argument in support of more stringent and ambitious control policies.

Box 1: Clean Air and Climate Solutions for ASEAN

In 2023, UNEP, ASEAN, and CCAC released a report entitled: 'Clean Air and Climate Solutions for ASEAN'. The report identifies 15 solutions—12 of which overlap with the solutions in this cost of inaction assessment—that were selected based on their potential to deliver the maximum reduction in ASEAN population's exposure to $PM_{2.5}$. In fact, full implementation of these solutions can reduce population weighted $PM_{2.5}$ average concentrations across the ASEAN region by 50 to 70 percent by 2030. Further, the 15 solutions would also deliver important climate co-benefits from the reduction of SLCPs. The solutions involve actions in many sectors, ranging from conventional industrial process controls to shifts in diets and agricultural practices. They would also gain momentum and thereby reduce the costs of inaction from efforts to strengthen governance, increase finance, and enhance regional cooperation.

1.2. Objective

Through quantifying the costs of not acting on air pollution, this assessment aims to increase the evidence base to support policymakers and decisionmakers in Indonesia to take further action and prioritize ambitious policies and cost-effective measures to improve air quality. It provides an initial quantification of some of the costs of inaction from tackling air pollution in Indonesia, through quantifying and costing the health benefits which could be achieved from implementing 12 specific mitigation solutions. It also highlights some other benefits, such as for climate change, which could be achieved if these solutions are implemented. Through comparing the quantified health impacts from air pollution exposure in the baseline scenario, representing current policies, with a 'strong mitigation' scenario in which 12 additional ambitious solutions are implemented, some of the costs of not acting on air pollution are directly quantified. This assessment therefore gives an initial indication of the future costs which Indonesia will experience if no further action is taken and highlights specific solutions which, if implemented, could significantly reduce these costs in the future. This approach takes a different perspective in comparison to a typical air pollution mitigation assessment, which normally focuses on the benefits of action rather than the costs of not acting. The aim of this assessment is therefore to provide a strong motivation and justification for further action and allow for the development, prioritization and implementation of cost-effective, progressive and integrated policy measures to tackle air pollution with benefits for health and climate.

1.3. Approach

The 'cost of inaction' is defined here as the damage cost that will remain without policy intervention, or conversely, as the damage cost that can be avoided by taking action. The cost is related to the key impacts that are associated with air pollution and their total damage costs. The assessed and monetized impacts can include direct health costs, lost labour days, mortality costs, declining crop yields, ecosystem impacts, material damage, impact on tourism, noise, visibility, traffic accidents and congestion.

A simplified, conceptual representation of the approach used in this assessment is shown in Fig 1.1. The key principle is the comparison of two different scenarios for a given target year: Current Policies scenario, representing the implications of current legislation (assuming no further policy action), is compared to an alternative Additional Policies scenario in which a bundle of new measures to curb pollution, reduce GHGs, and address SDGs are implemented.

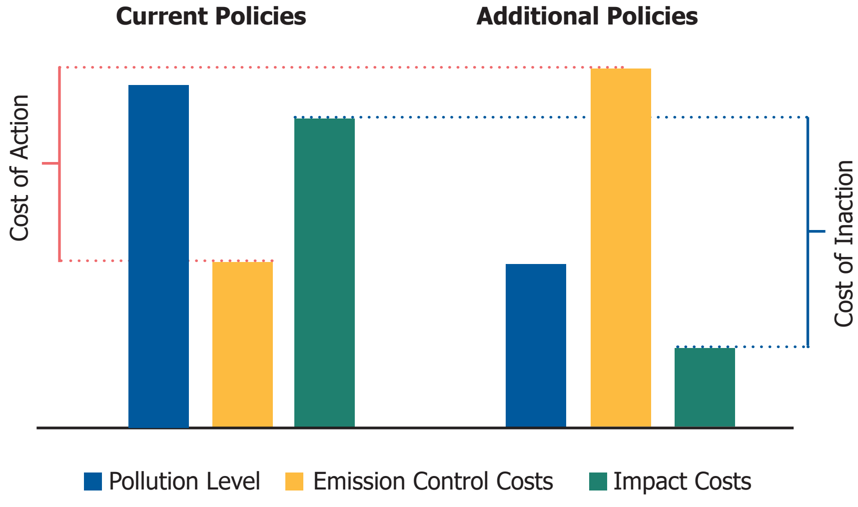

Fig. 1.1 *Schematic picture of the proposed approach for quantifying the cost of action vs cost of inaction, relying on the comparison of Current Policies and Additional Policies*

The Current Policies case is associated with a certain level of ambient air pollution (symbolized by the black bar in Fig. 1.1), costs for implementation of existing pollution legislation (the orange bar), and a certain level of related costs (the blue bar) from air pollution, which is here expressed in monetary terms. In the Additional Policies case, the emission control costs are higher while pollution levels and associated impact costs are lower. The costs of action are then defined as the difference between the emission control costs in the Current Policies and Additional Policies scenarios, whereas the costs of inaction are the difference between the impact costs or, in other words, the forgone or 'lost' monetized benefits if no action is taken.

1.4. Methodology

The analysis in this assessment employs the Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model (Amann et al., 2011; UNEP, 2019) developed at the International Institute for Applied Systems Analysis (IIASA) (see Box 2 and Fig. 1 in the Annex). GAINS is an integrated assessment model quantifying emissions of various air pollutants at a granular sectoral level, ambient concentrations of $PM_{2.5}$ and the associated mortality. For the purpose of this assessment, the model framework has been further developed and extended to include additional health endpoints, impacts on workforce, and respective costs.

The assessment quantifies health impacts in terms of mortality and morbidity from ambient $PM_{2.5}$. Impact costs are quantified as the monetary value per year of life lost (as estimated from willingness-to-pay studies) and the health system costs of morbidity. Concentration-response functions (CRFs) for several morbidity outcomes were generated from a dedicated meta-analysis from international studies; mortality calculations follow the Global Burden of Disease (GBD) methodology. Input data for the calculations (such as baseline incidence rates, cost parameters) were assembled from local sources where available and supplemented with data from international sources in other cases. Details of the methodology and data sources are explained in the Annex.

Box 2: The GAINS model

The GAINS model explores cost-effective multi-pollutant emission control strategies that meet environmental objectives on air quality impacts (on human health and ecosystems) and GHGs. GAINS, brings together data on economic development, the structure, control potential and costs of emission sources, the formation and dispersion of pollutants in the atmosphere and an assessment of environmental impacts of pollution (https://gains.iiasa.ac.at/models).

Emissions are estimated using the GAINS emission factor database that has been peer-reviewed and compiles both national and international data on source- and technology-specific measures; more than 1000 measures to control emissions are represented. The mitigation options include impact on emissions of all key air pollutants (sulfur dioxide (SO_2), nitrogen oxides (NO_x), PM (including black carbon (BC) and organic carbon (OC)), non-methane volatile organic compound (NMVOC), ammonia (NH_3) and GHGs.

The model computes the atmospheric dispersion and formation of secondary pollutants for defined scenarios. This allows the quantification of $PM_{2.5}$ concentrations and their changes from application of each measure/solution at a resolution of 0.1°×0.1° or roughly 10x10km. Overlaid with population at the same resolution, the exposure distribution to ambient $PM_{2.5}$ in the population is calculated. Applying CRFs from the international literature, GAINS calculates premature mortality from long-term exposure to $PM_{2.5}$, and the associated life years lost (YLLs). For this analysis, the model has been extended to include other health related impacts, i.e., morbidity, work time loss, their costs, etc. (see Fig. 1 in the Annex). Details of the methodology are explained in the Annex.

1.5. Scenarios

To calculate the cost of inaction from air pollution, as illustrated in Fig 1.1, this assessment directly quantifies the differential impacts and costs due to the health impacts of air pollution exposure for two alternative future scenarios. The first, or 'Current Policies' scenario, assumes that only current legislation and policies related to air pollution are implemented. While, the additional policies or 'Strong Mitigation' scenario, directly assumes the implementation of 12 additional ambitious clean air solutions, which have been identified and developed within the Clean Air and Climate Solutions for ASEAN study (UNEP/CCAC, 2023), and which draw on concepts applied in the UNEP/CCAC Assessment for Air Pollution in Asia and the Pacific (Amann et al., 2019; UNEP, 2019). A broad description of the underlying scenarios for the ASEAN region is provided in the Annex.

Emissions into the future for both scenarios are dependent on changes in activity which themselves are a product of key sociodemographic and macroeconomic drivers. Both scenarios assume that Indonesia will experience significant economic development in the future with its GDP growing by about 95% to 2030 from 861 billion US$ in 2015, following the projections made in the International Energy Agency's World Energy Outlook 2018 (IEA, 2018). The population of Indonesia is also assumed to change into the future, growing from 258 million in 2015 to 296 million in 2030 and 322 million in 2050, following the United Nations (UN) World Population Prospects 2017 (UN, 2017), Medium Scenario. At the same time, the Indonesian population is projected to age significantly, which has a considerable effect on the health impact calculations undertaken in this assessment.

The **Current Policies** scenario that is used as a baseline in this assessment is a rather conservative benchmark for future development. It considers only policies which have already been implemented or agreed in Indonesia by mid-2020. The information about current policies, emission limit values and standards is taken from Zhang (2016), Motokura et al. (2017), TransportPolicy.net[1] (n.d.), Organization for Economic Co-operation and Development (OECD) (2019), Acid Deposition Monitoring Network in East Asia [EANET] (2020), He et al. (2021), and Lestari et al. (2022). The energy trends used in the Current Policies scenario are consistent with the IEA 'New Policies' scenario (NPS), and air pollution controls are implemented to the extent foreseen under current legislation, but no further action is taken. Some of the above studies also provide assessment of progress in implementation of policies, which is important to create a more realistic outlook of impacts from introduction of existing legislation and assessment of future mitigation potential; reported experience is reflected in the modelling approach used in this assessment.

In contrast to this, **the Strong Mitigation** scenario (additional policy scenario in above Fig. 1.1), assumes that the additional 12 key solutions[2] developed under the Clean Air and Climate Solutions for ASEAN study (UNEP/CCAC, 2023) are effectively implemented to the maximum extent possible. These solutions are not individual actions but rather a bundle of actions relating to similar technologies or sectors (e.g., for road transport, strengthened emission standards and increased population of electric vehicles is one solution) (Fig. 1.2/Infographics[3]) and have been selected based on their potential to deliver the maximum reduction in the population's exposure to $PM_{2.5}$. The selected solutions combine application of technological solutions to reduce emissions as well as exploit potential for the energy efficiency, fuel switching, renewables and electrification of vehicle fleet as identified in the IEA Sustainable Development Scenario (SDS). Furthermore, diets, and hence agricultural production, are in line with the Lancet EAT Planetary Diet (Willett et al., 2019). Further details on the solutions included in this assessment can be found in the Annex and in UNEP/CCAC (2023) report. As well as calculating the total combined impact of implementing all 12 solutions (Fig. 1.2), each individual solution is also independently quantified in terms of their impacts on $PM_{2.5}$ exposure, this can help to identify those solutions which could have the largest impact on improving air quality. As shown later in this assessment, several of these measures also bring strong co-benefits including reduction of GHGs emissions and contribute to the achievement of several SDGs.

[1] For more details, refer to: https://www.transportpolicy.net/standard/indonesia-fuels-diesel-and-gasoline/.

[2] The UNEP/CCAC Assessment on Clean Air and Climate in the ASEAN investigates 15 solutions, some of which however do not directly influence air pollution levels. This study includes the 12 solutions relevant for $PM_{2.5}$ concentrations.

[3] More detailed information about the 12 solutions is provided in Table 1 in the Annex.

* The future potential shown includes the potential scope for what accelerated electrification of vehicle fleet can achieve, i.e., most likely less than half of that could be achieved by electrification by 2030.

** Improvements to coal, oil and gas production and distribution, including through reducing leaks and utilizing captured gas.

Fig. 1.2 *12 key solutions to address exposure to fine particulate matter in ASEAN*

2. Results

This section presents results from the assessment itself. Section 2.1 quantifies the emissions and ambient $PM_{2.5}$ concentrations in the Current Policies scenario and the Strong Mitigation scenario. Section 2.2 then quantifies health impacts and costs of inaction for individual measures contained in the Strong Mitigation scenario, and Section 2.3 analyzes co-benefits of measures for climate change mitigation.

2.1. Emissions and ambient concentrations

2.1.1 Current policies scenario

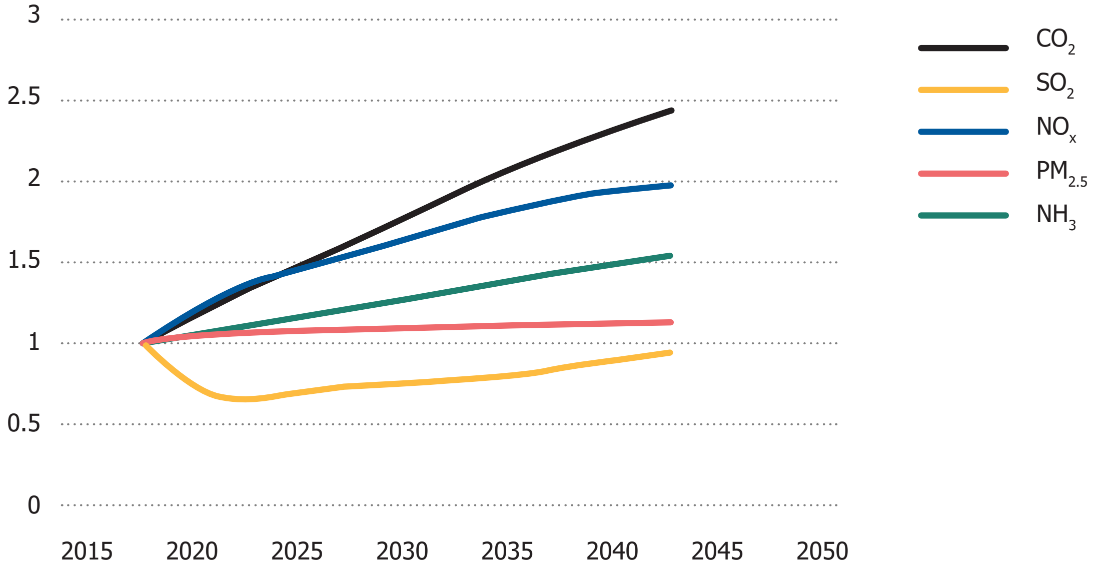

Fig. 2.1 *Trends in emissions of CO_2 and air pollutants in the Current Policies scenario for Indonesia*

In the Current Policies scenario, the assumed implementation of existing and recently introduced legislation in the power, industry and transport sectors already shows some effect at slowing the growth of emissions of $PM_{2.5}$ and key PM precursor pollutants SO_2, NO_x, (Fig. 2.1). In fact, these precursors are growing slower than carbon dioxide (CO_2), suggesting gradual decoupling of economic growth from air pollutant emissions. The main contributions and growth of CO_2 emissions in Indonesia are from power and industry sectors. However, current policies are not sufficient to offset the increase in fuel use and production activities, which combined with assumed strong economic growth in Indonesia drives the significant increases in CO_2 emissions (Fig. 2.1). Another notable trend in the baseline involves the residential sector. For primary $PM_{2.5}$ emissions, cooking and lighting contributed about 30% of $PM_{2.5}$ in 2015, according to GAINS model estimates, successful policy virtually eliminating use of kerosene for lighting and a trend towards clean fuels for cooking (providing access in both urban and rural areas) is expected to result in decline of emissions from this sector reducing its share to less than 20% and 10% by 2030 and 2050, respectively, and contributing near stabilization of overall $PM_{2.5}$ emissions (Fig. 2.1).

Annual mean $PM_{2.5}$ concentrations in Indonesia estimated by GAINS for 2015 are between 5 and 80 $\mu g/m^3$ (Fig 2.2, top panel). The pollution problem is very unequally distributed across the country, with the densely populated island of Java suffering the highest concentrations. The capital region around Jakarta in the West of Java is most severely polluted, with annual mean concentrations estimated higher than 80 $\mu g/m^3$ in individual locations, followed by the area around Surabaya. Outside Java, the highest concentrations are seen in large cities such as Medan, Makassar, Palembang, Bandar Lampung, Pontianak or Banjarmasin. Outside large cities, only Sumatra faces elevated concentrations, while much of the outer islands enjoy clean air even below the 2021 World Health Organization (WHO) Guideline level of 5 $\mu g/m^3$, consistent with the low population density there. A validation against available monitoring data is provided in the Annex .

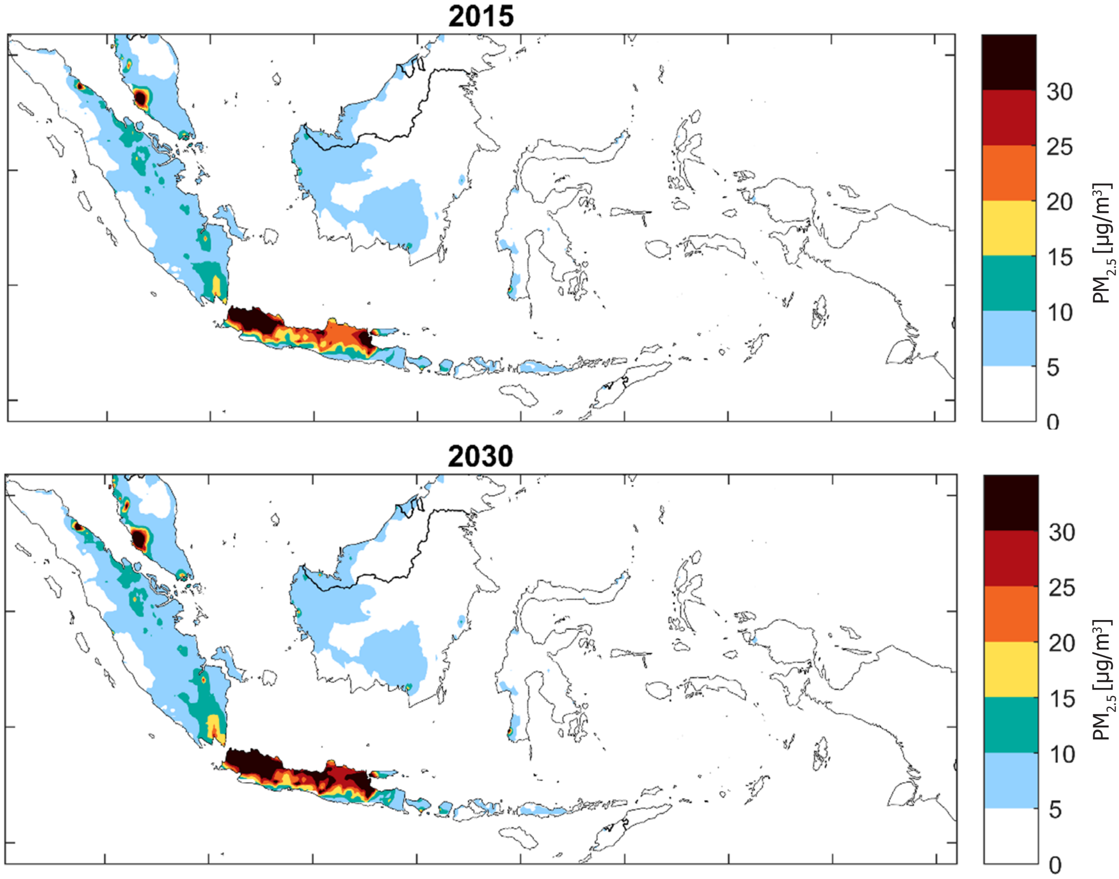

Fig. 2.2 *$PM_{2.5}$ concentrations for Indonesia modelled with the GAINS model for 2015 (top) and for 2030 under Current Policies (bottom)*

Even assuming the successful implementation of existing policies and legislation, the situation in populated areas, is expected to get worse by 2030 in the Current Policies scenario (Fig. 2.2, bottom panel). This is also illustrated in Fig. 2.3, which shows the distribution of population exposure to $PM_{2.5}$. In 2015, 86% of the population was exposed to $PM_{2.5}$ levels above the current WHO air quality guideline of 5 µg/m^3 and 67% was exposed to levels above the 2005 WHO guideline of 10 µg/m^3 (now Interim Target 4), 30% between interim targets 1 and 3 (15-35 µg/m^3), and 25% at concentrations higher than 35 µg/m^3. In the Current Policies scenario, the situation is not expected to improve by 2030. Even with assumed effective implementation of current legislation, more than 87% of population could be experiencing still concentrations above the 2005 WHO guideline and the number exposed to concentrations exceeding 15 µg/m^3 would grow from 131 to more than 180 million owing to increasing concentrations in some regions (Fig. 2.2.) as well as continuing urbanization.

2.1.2 Additional policies

The full extent of conceivable action against increasing air pollution levels is explored in the Strong Mitigation scenario. This is an extremely ambitious scenario, which would require ambitious goal setting and immediate strong policy action to take advantage of all 12 mitigation solutions illustrated in Fig. 1.2 and listed in Table 1 (Annex). As illustrated in Fig. 2.3, implementing all 12 of these solutions in the Strong Mitigation scenario, would mean that by 2030, more than 100 million people would enjoy PM concentrations below the current WHO guidelines and only 37% would be exposed to levels above 10 µg/m^3. The Current Policies and the Strong Mitigation scenarios constitute the extreme ends of a spectrum of possible scenarios between business as usual and extremely ambitious mitigation. Within this range, a more realistic policy scenario would apply policies to some degree to exploit much of the potential while keeping policy costs limited. To identify which of the 12 solutions have the largest impact, within this analysis we quantify the individual potential of each individual solution to improving air quality.

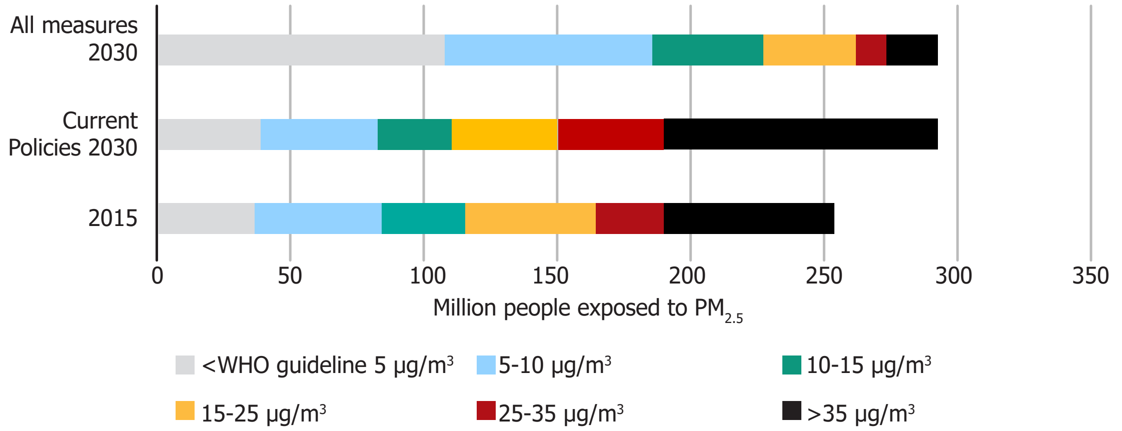

Fig. 2.3 *Population exposure to $PM_{2.5}$ modelled with the GAINS model for 2015 and for 2030 under different scenarios*

Fig 2.4 shows the contribution of each of the 12 solutions to improved air quality in terms of population-weighted mean $PM_{2.5}$ concentrations in Indonesia in 2030, assuming the full implementation of each solution both in Indonesia but also across the whole ASEAN region. This figure also shows the impact on exposure from measures which had already been implemented by 2015 (blue), and have already contributed to improved air quality, with those that have been included in recent legislation passed after 2015 but may not yet fully implemented (green), potentially contributing to future improved air quality if successfully implemented. The further potential (yellow) for each solution would therefore come from implementing the highest level of ambition. The aim of this analysis is to show in which areas or sectors progress has already been taken and where there remains the most potential for further ambition through implementation of the solutions.

Controls on $PM_{2.5}$ and SO_2 emissions from electricity generation and industry have already contributed to large improvements in air quality in Indonesia, estimated to have already resulted in 5 µg/m³ reduction in population weighted $PM_{2.5}$ concentrations compared to if no policies or controls were implemented in these areas, while implementation of stricter emission standards for vehicles has also effectively reduced air pollution concentrations by almost 9 µg/m³ (dark blue and green parts of the bars). Despite the success in some areas, Fig. 2.4 shows that there is a large potential for further improvements (yellow) which is the focus of the analysis presented in the remaining part of this report. The largest areas where there is additional potential for improving air quality are in the transport sector (including electrification of road transport, strict standards on remaining internal combustion vehicles and their enforcement through regular inspection and maintenance), further measures controlling large point sources such as power and industry (including a transition to renewable energy and efficiency improvement), improved waste management (elimination of open waste burning), as well as better agricultural practices which minimize nitrogen losses.

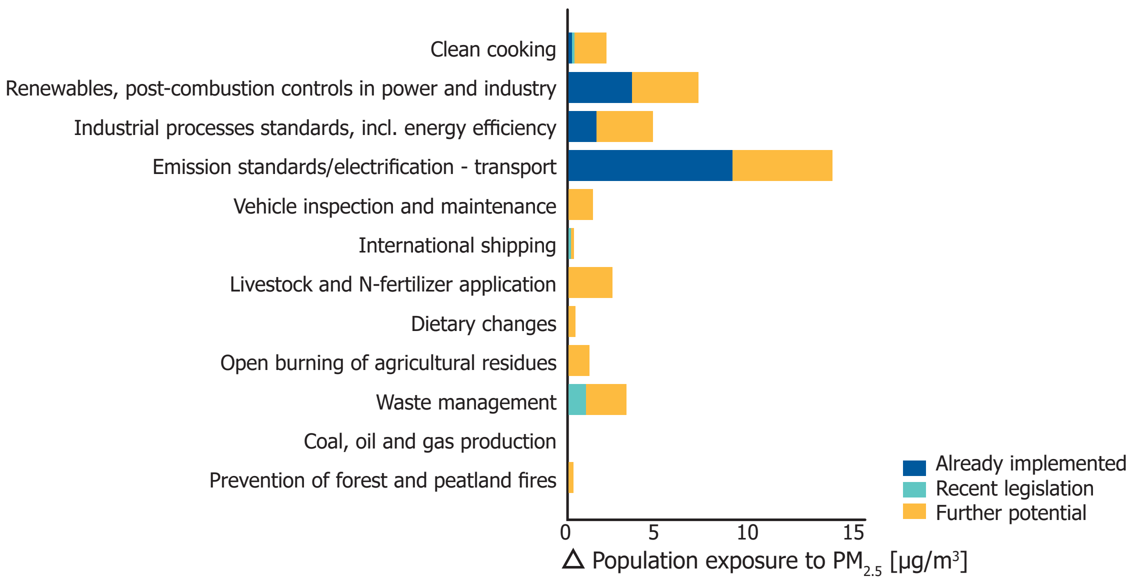

Fig. 2.4 *Expected improvement in population-weighted mean $PM_{2.5}$ concentrations in Indonesia from each of the 12 solutions in 2030, distinguishing already implemented measures (dark blue), legislation passed after 2015 but not yet fully implemented (green), and the further potential (orange)*

2.2. Health impacts and cost of inaction

Exposure to $PM_{2.5}$ leads to considerable health impacts in Indonesia. The GAINS model estimates that in 2015, more than 127,000 premature deaths were attributable to ambient $PM_{2.5}$, corresponding to 2.2 million YLLs. In the Current Policies scenario, due to increases in $PM_{2.5}$ concentrations, as well as population aging, the mortality burden is projected to increase to 217,000 premature deaths and 3.5 million YLLs in 2030.

At the same time, $PM_{2.5}$ also contributes to a significant burden of morbidity. Numbers of morbidity and mortality attributable to $PM_{2.5}$ exposure estimated in 2015 and under the Current Policies scenario in 2030 are given in Table 2, along with their monetized values and the unit costs used for the calculation. For mortality, either the number of premature deaths can be used in conjunction with the value of a statistical life (VSL), or the number of YLL in combination with the value of a life year (VOLY). As is usually the case, we find that the approach via deaths × VSL gives a higher cost than YLLs × VOLY, reflecting some of the difficulties with attaching a monetary value to human life. For all further analysis shown in this report, we use the YLL monetization approach for valuating loss of human life.

Unit costs, VSL and VOLY shown in Table 2 are combining national data and internationally available data sets adapted to Indonesia's per-capita GDP; details are described in Annex 1.

Table 1. *Morbidity and mortality attributable to ambient $PM_{2.5}$ in Indonesia in 2015 and 2030 under current legislation, and their costs. For mortality, premature deaths and YLLs are alternative indicators and are shown for comparison only*

Indicator	Current Policies		Strong Mitigation	Unit Cost $US 2015	Costs - Current Policies		Costs – Strong Mitigation
	2015	2030	2030		2015	2030	2030
	Cases - YLLs/year				Thousand $US 2015/year		
Mortality							
Premature deaths	127,178	216,032	83,295	249,284	31,703,495	53,853,414	20,764,147
YLLs	2,196,731	3,500,409	1,377,596	9,427	20,707,914	32,997,285	12,986,176
Morbidity							
Asthma (Emergency Room Visits), all age	17,778	27,847	9,337	11	189	295	99
Cardiovascular hospital admissions, below 65 years of age	8,656	13,301	4,174	1,152	9,976	15,329	4,810
Cardiovascular hospital admissions, post 65 years of age	4,980	12,716	4,225	1,152	5,739	14,655	4,869
Respiratory hospital admissions, all age	13,998	22,017	7,314	561	7,846	12,341	4,100
Respiratory restricted activity days, working age	259,084,841	438,353,537	137,800,276	23	6,020,742	10,186,676	3,202,271

Fig. 2.5 shows the total costs due to morbidity and mortality impacts from air pollution exposure in 2030 in the two alternative future scenarios considered in this assessment. In the Current Policies scenario, by 2030, the health damage costs alone in Indonesia are estimated to reach over 43 billion USD per year, a value equal to 2.6% of Indonesia's GDP. In contrast, in the Strong Mitigation scenario, due to the success of the 12 clean air solutions in reducing $PM_{2.5}$ concentrations, this cost is estimated to decrease to approximately 16.2 billion USD per year, equivalent to about 1% of GDP in 2030. Therefore, this means that by not implementing the 12 clean air solutions and acting on air pollution, the cost of inaction in Indonesia is estimated to be 27 billion USD per year, equivalent to around 1.6% of GDP in 2030. These costs, relating only to the health burden of air pollution exposure are an indication of the large costs which could be avoided if action on air pollution is taken.

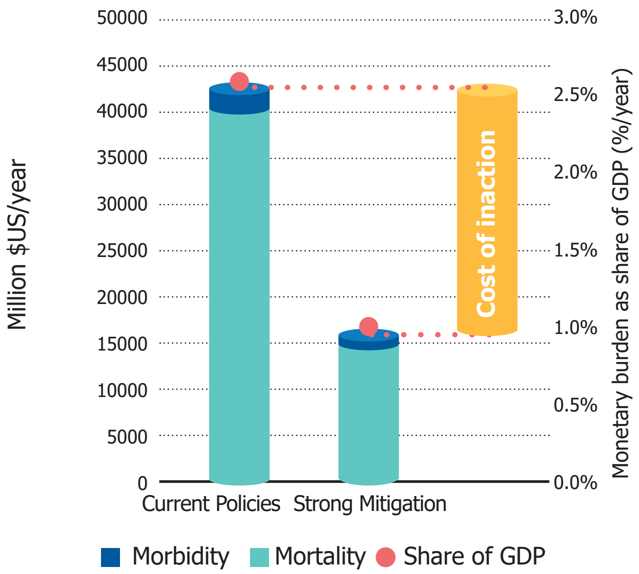

Fig. 2.5 *Monetized health burden from $PM_{2.5}$ exposure in 2030, comparing the Current Policies scenario, and effective implementation of all measures assessed in this study for Indonesia (Strong Mitigation case). Stacked Bars – Left axis: Burden expressed as million USD per year, Red dots – Right axis: comparison to GDP*

The majority of the economic burden is associated with mortality (shown here is monetized estimate for YLL) representing about 80% of costs. The remaining 20% are dominated (99%) by costs associated with respiratory restricted activity days, i.e., working day losses (Fig. 2.6).

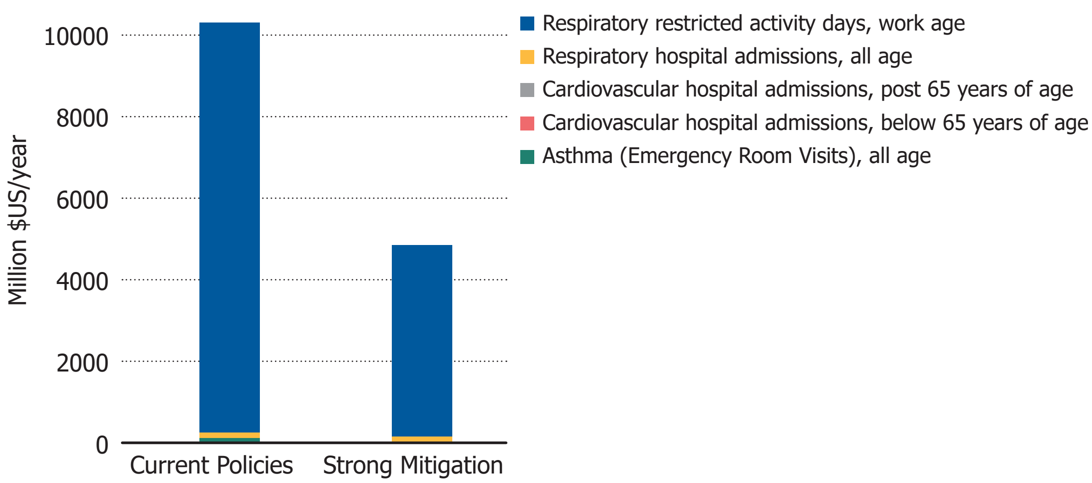

Fig. 2.6 *Monetized morbidity burden from $PM_{2.5}$ exposure in 2030, comparing the Current Policies scenario, and effective implementation of all measures (Strong Mitigation scenario)*

Fig 2.7 provides a summary of premature death, hospital admissions, and working days lost due to ambient $PM_{2.5}$ as estimated for 2015 and expected development towards 2030 in the Current Policies scenarios as well in the Strong Mitigation scenario where all the proposed measures are taken. It was estimated that in 2015, around 18,000 asthma related emergency room visits, over 13 thousand hospital admissions for cardiovascular reasons, 14,000 respiratory related hospital admissions, and 259 million days of restricted activity for respiratory reasons among the working age population are attributed to $PM_{2.5}$ exposure. In the Current Policies scenario, these health impacts are projected to increase, while implementing all 12 solutions in the ambitious Strong Mitigation scenario could effectively reduce total hospital admissions by around 32 thousand as well as reducing the number of emergency room visits from asthma by 18 thousand and avoiding 132 thousand premature deaths (Fig. 2.7).

Beyond the analysis of impacts for policy introducing 12 solutions as a whole (Fig. 2.5), we also quantify the specific health benefits in monetary terms from implementing each of the individual solutions included in the Strong Mitigation scenario. These health benefits can be also seen as the cost of inaction for each solution if they are not implemented. This can be useful for understanding which measures or solutions will have the largest health benefits and avoided costs, and could also be compared against the costs for implementing each solution if such data becomes available. Fig. 2.8 shows that the largest benefits are expected from electrification and emission standards in road transport for which monetized benefits are estimated at about 14.7 billion USD, with stricter vehicle inspection and maintenance adding further 3.5 billion USD. Increasing renewables and applying post combustion controls in the power and industrial sectors as well as improving industrial production standards could bring benefits of 18.2 billion USD. While combined, the three agricultural solutions of reducing agricultural residue burning, dietary shifts and more efficient fertilizer application and livestock management practices could also bring benefits worth about 10.3 billion USD. Solutions which improve municipal waste management could result in benefits of 5.9 billion USD per year, a complete transition to clean cooking could result in benefits of 4.8 billion USD per year from ambient $PM_{2.5}$ only[4], and improved enforcement of forest fire prevention could result in health benefits in order of 0.5 billion USD, on top of benefits from avoided ecosystem damage.

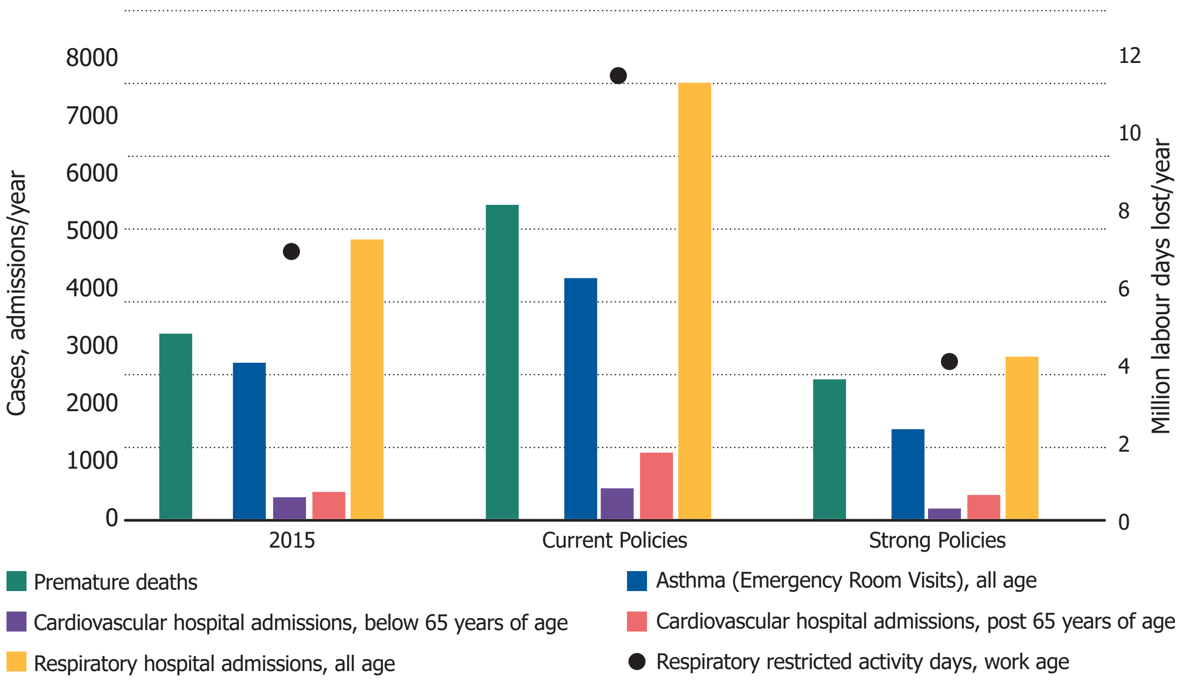

Fig. 2.7 *Summary of the incidence of included impacts estimated for 2015 and analyzed scenarios. Deaths, emergency room visits and hospital admissions are shown on the left axis, restricted activity days (dots) use the right axis*

[4] Note that this estimate includes only the monetization of health impacts from ambient $PM_{2.5}$. Additional benefits would be expected from indoor air pollution reductions in the measure Clean Cooking.

Fig. 2.8 distinguishes the benefits gained from implementation of measures in Indonesia (blue), and in the other ASEAN countries (yellow). Due to Indonesia's location and size, the influence of transboundary inflow of pollution as well as the benefits which can be reaped through other countries' implementing measures are limited. It is likely, however, that Indonesia's influence on neighbouring ASEAN countries is larger than the other way, and therefore neighbouring countries would benefit from implementation of ambitious air quality actions in Indonesia.

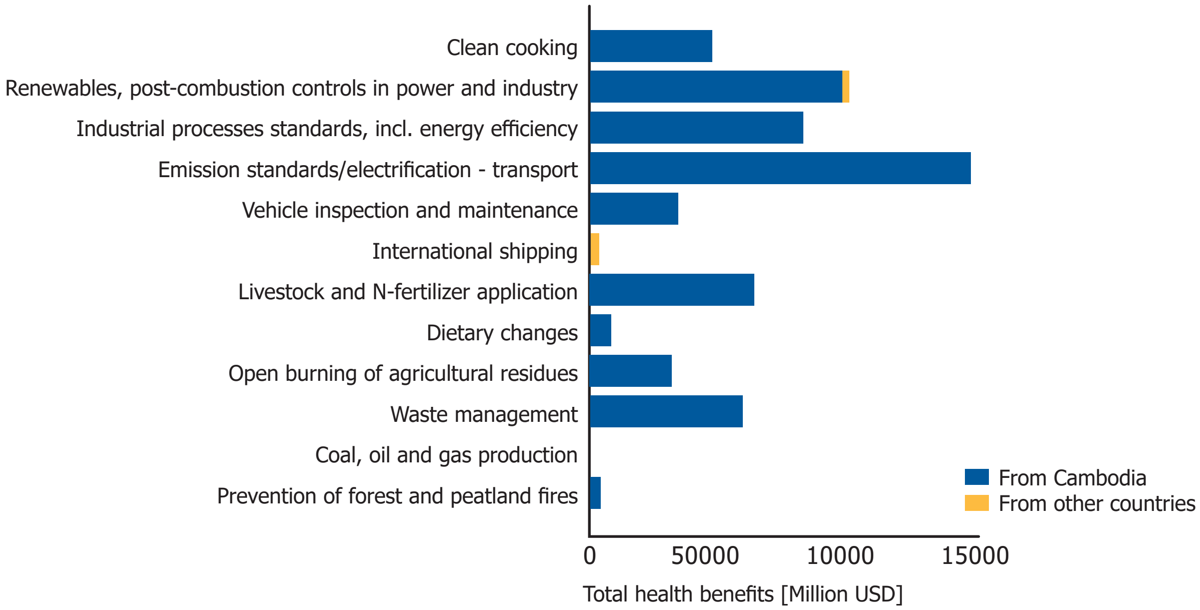

Fig. 2.8 *Monetized health benefits from individual measures applied in 2030 on top of current policies*

2.3. Climate and other co-benefits

This assessment has estimated the costs that Indonesia will experience in the future if no further action is taken due to the increasing health burden of air pollution. It has also shown the large benefit for air quality and health in Indonesia which could be realized through the implementation of ambitious clean air solutions. Implementing the 12 clean air solutions are likely to also have multiple other additional benefits beyond reducing emissions and concentrations of air pollutants, these include benefits for climate change through reducing GHG emissions. Fig. 2.9 shows the potential for each of the individual clean air solutions to reduce GHG emissions and specifically compares $PM_{2.5}$ concentration reductions with emission reductions for CO_2 and methane (CH_4) (converted to CO_2-equivalent emissions using Global Warming Potential (GWP)-100) from implementing each solution.

In 2030, the largest potential for reducing GHG emissions are for the solutions related to power, transport and industry sectors. The measure which has the largest potential to reduce GHG emissions is introducing renewables in the power sector. This, combined with strict post-combustion emission controls, is estimated to reduce GHG emissions by more than 100 Mt (CO_2-eq.) by 2030 and more than 400 Mt (CO_2-eq) by 2050, while simultaneously reducing population weighted $PM_{2.5}$ exposure by 4 µg/m^3 by 2030 and 6 µg/m^3 by 2050. In addition, the measure which has the largest potential for reducing air pollution also has significant climate co-benefits: introducing more stringent emission standards and accelerating electrification in the road transport sector could simultaneously reduce GHG emissions by 35 Mt (CO_2-eq.) by 2030 and 150 Mt by 2040, while also decreasing population average exposure to $PM_{2.5}$ by more than 5 µg/m^3 by 2030 and 13 µg/m^3 by 2050. It is also likely that for road transport, comparable benefits could be achieved by demand side policies, including improved public transport, low emissions (car free) zones, congestion charging schemes, developing new bike lanes and incentivize active mobility, etc. Such policies could at the same time have multiple other co-benefits such as reducing congestion and time spent in traffic jams, reduced number of road accidents, as well as additional health co-benefits from active travel.

The analysis presented in this report focuses primarily on benefits that can be achieved in the near term, typical air quality policy time horizon. Climate policies set longer-term targets and respective transformational measures require often longer time to be fully implemented. Fig. 2.9 shows both the air quality and climate co-benefits achievable in the near term (by 2030) as well as by 2050 to highlight co-benefits of transformative changes in the longer term. A longer time perspective helps to appreciate better the co-benefits of some measures like electrification of the transport sector, which have a longer inertia due to fleet turnover, and large-scale deployment of renewables in power and industry. Conversely, inaction in these sectors would also forgo the substantial GHG reductions and thus have a 'cost of inaction' in terms of emissions, which can also be associated with a monetary cost if a carbon price is introduced.

Indonesia has set ambitious targets to reduce GHG emissions in the country by at least 31% in 2030 compared to a baseline scenario, while simultaneously aiming to becoming a fully developed economy by 2045. Both climate change and air pollution have economic costs, and policies such as those highlighted above, could therefore have substantial benefits for both the health and wellbeing of the population but also in aiding economic development and achieving the SDGs. At the same time, some policies relating to climate or sustainable development such as those detailed in Indonesia's Nationally Determined Contribution (NDC) or Long Term Development Strategy will also have co-benefits for air pollution, quantifying these additional health and economic benefits could enhance the evidence base and provide further motivation for action.

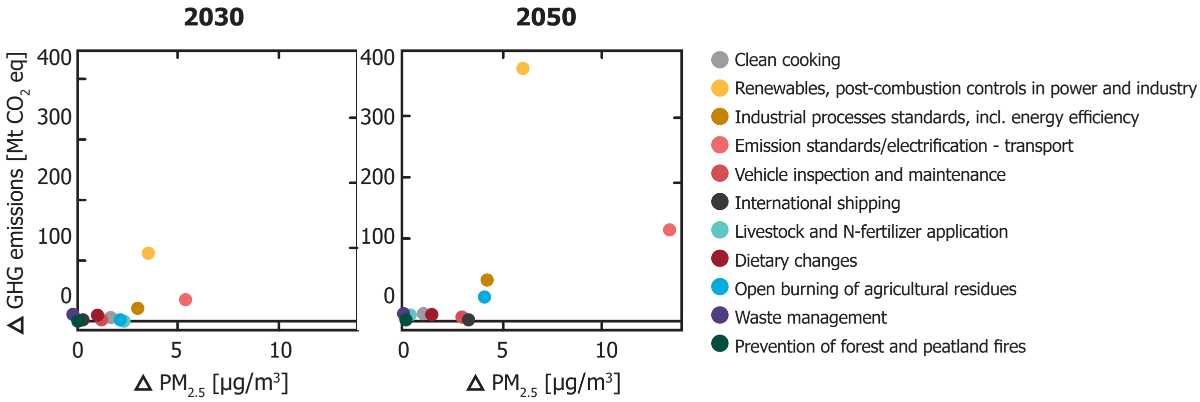

Fig. 2.9 *Co-benefits of individual measures for GHG emissions (CO_2 + CH_4) when fully implemented in 2030 (left) and 2050 (right)*

3. Limitations

3.1. Scenarios and solutions

The analysis presented in this report relies on existing scenarios; development of completely new scenarios fit for analysis with the GAINS model was not feasible due to available resources. However, the available scenarios reflect a broad range of interventions with respect to impacts and are expected to cover the potential scope of local policies. Reviews and assessments of state of policies and progress in their implementation (UNEP, 2015; OECD, 2019; EANET, 2020) show that the assumptions about policies considered in the Current Policies scenario are largely complete and consistent with the existing legislative framework in Indonesia addressing air quality and climate change. Even though, some of the most recently decided policies considered for implementation in the coming years are not included in the current policy case (e.g., transport fuel standards[5,6]), their reduction potential is captured in the further mitigation potential estimated in the assessment. The same applies to proposed or evaluated potential and impacts of mitigation of air quality (e.g., Greenstone and Fan (2019)) as the respective mitigation potentials are well represented in the Strong Mitigation scenario.

The default temporal model resolution is five years and although the analysis can be done for single or individual years, the available set of scenarios does not have finer resolution. The respective assessments are aiming at demonstration of benefits (assessment of cost of inaction) in a longer-term perspective, which is consistent with typical responses to policy actions.

3.2. Data availability/reliability

There are several limitations due to available data, tools as well as available resources. The quality and representativeness of the results and assessment critically depends on the underlying data on baseline rates of mortality, morbidity, and costs. While the default data set generated from international sources is scientifically robust, it is not necessarily fully representative of the local circumstances, and local data are clearly preferable. The assessment is currently based on a combination of local and international data.

3.3. Modeled $PM_{2.5}$ concentrations

GAINS reproduces measured ambient $PM_{2.5}$ concentrations in the less polluted regions of the country well, but seems to overestimate concentrations in the Western Java region around Jakarta. This may lead to an overestimate in health impacts and damage costs since this is one of the most populated areas of Indonesia. Attributable deaths estimated for current levels of $PM_{2.5}$ are slightly higher than the estimate of the GBD by 11%.

3.4. Costs of action

While the assessment focuses on costs of inaction, an estimate of the cost of action (including both current policies as well as further mitigation measures' implementation) has not been undertaken in this assessment and would require further discussion with national experts to validate and extend valuation of measures.

The GAINS model routinely quantifies annualized costs for implementation of technical ('end of pipe') air pollution control measures. A holistic assessment should also include costs for structural transformations such as, for example, decarbonization of the energy sector, which is quantified in the energy system models, typically used as source of the energy use scenarios in the GAINS model. Further costs associated with transformation to low pollution economy might include costs of providing access to clean energy for cooking, improvement of waste management, transformation of agricultural production system, and costs of enforcement of considered legislation. A preliminary estimate in GAINS, considering only technical mitigation options and assuming international costs, indicates annualized costs for additional measures (Stringent vs Current policy cases) in order of 8-10 billion USD, which represents about a third of the estimated cost of inaction. However, as noted earlier,

[5] For more details, refer to: https://www.transportpolicy.net/standard/indonesia-fuels-diesel-and-gasoline/.

[6] For more details refer to: https://www.reuters.com/business/energy/indonesia-bar-sale-gasoline-below-90-octane-2023-regulator-2022-10-26/.

this estimate does not include costs of transformation towards higher share of renewables, alternative diets, etc.

In summary, in terms of cost of action estimation, there are number of limitations in the models and data:

i. GAINS relies on international defaults for costs and does not include local cost factors where appropriate (although, most air pollution control technology is traded internationally),

ii. GAINS covers only costs for technical air pollution control measures and not the system costs for energy transition, dietary changes, institutional costs, etc., and

iii. it assumes full implementation even of very costly technologies which would be left out in a cost-effective scenario.

3.5. Scope of impacts assessed

The range of possible costs on the impacts side, used for quantifying the 'costs of inaction', is large. Beyond monetized mortality costs and market costs for morbidity, they can include other macroeconomic and environmental costs such as:

- Crop losses associated with elevated ozone,
- Ecosystem impacts from air pollution (Sulfur and Nitrogen deposition),
- Macroeconomic impacts of loss of labour force.

The analysis in this assessment is limited to costs of mortality and morbidity, and to only ambient concentrations of $PM_{2.5}$. Only some morbidity outcomes are considered, so the total impact via morbidity is likely underestimated. Exposure to other air pollutants like nitrogen dioxide (NO_2) and O_3 is associated with health and ecosystems impacts and crop loss due to elevated O_3 concentrations. O_3 formation is influenced by CH_4 emissions and therefore introduction of measures analyzed in this assessment can bring additional co-benefits. However, these are orders of magnitude smaller than the PM reduction related benefits and are not reported here.

Impact from deposition of sulfur and nitrogen, e.g., acidification and eutrophication of ecosystems, could be significant and the measures analyzed in the assessment would bring reductions of SO2, NO_x, and NH_3 emissions contributing to reduced deposition and consequently leading to at least partial recovery of ecosystems in the long-term. However, lack of consistent datasets on ecosystem sensitivity across the region as well as costs assessments for associated impacts does not yet allow for such analysis.

Finally, the assessment of macroeconomic impacts and benefits using macroeconomic models was beyond the resources available for this study and would require involvement of respective economic modelling team equipped with appropriate tools and data.

4. Conclusion and recommendations

Indonesia bears a high health burden from exposure to ambient $PM_{2.5}$ from both mortality as well as morbidity. Impact costs associated with this burden are substantial. The efficient implementation of already passed legislation will be important to slow down or halt the increasing trends in emissions and air pollution impacts. However, if no further policies are introduced, decreases are not expected.

Building upon the assessment for clean air in the ASEAN region, this study identified significant mitigation potential consisting exclusively of proven technical and non-technical actions that, if fully implemented, would deliver significant reductions of air pollution and in the longer-term important climate co-benefits.

Lack of further action translates into 'cost of inaction' which has been estimated here considering mortality and morbidity due to air pollution. Such cost has been estimated at about 27 billion USD in 2030 with the majority costs associated with premature mortality. Introducing policies stimulating the rapid introduction of identified further mitigation measures would results in significant benefits at potentially much lower costs, although the latter was not fully estimated. A preliminary estimate of implementation costs of technical measures indicates that these would represent in 2030 less than a third of the cost of inaction.

Key policies delivering major benefits include:

- Power and industry: Accelerated transition to renewable electricity generation in conjunction with end-of-pipe air pollution emission controls, electrification in industry, optimized energy efficient production processes,
- Electrification of the vehicle fleet, stringent emission controls on the remaining combustion engines, including regular inspection and maintenance to eliminate high-emitting vehicles,
- More stringent emission standards for industry,
- Improved agricultural practices, including reducing emissions from livestock management and from fertilizer application as well as effective enforcement of ban on open burning of agricultural residues,
- A complete transition to clean cooking fuels, ideally directly to electricity,
- Efficient waste management, prevention of open burning of waste

Further actions driven by health concerns will bring also important climate co-benefits (reduction of GHG emissions), which will be larger in the long-term translating by 2050 into significant reductions of CO_2 and CH_4. Among the most important measures delivering these longer-term benefits are promotion of stronger employment of renewables in power sector, electrification of transport, and waste management policies.

Annexes

Annex 1. Methodology and data sources

Overview

The calculation of the attributable mortality and morbidity burden in the assessment follows a comparative risk assessment framework, which means that out of a total burden of disease (in terms of death, or cases of morbidity events), a certain share is attributed to exposure to $PM_{2.5}$. The necessary ingredients for this calculation are the ambient $PM_{2.5}$ concentrations, population at the same grid resolution, CRFs for the selected disease endpoints, and baseline rates for these disease endpoints. For the assessment of impact costs, unit costs for the same are needed.

A chart of the information flows and calculation steps is shown in Fig. 1. The GAINS model (Amann et al., 2011; online at http://gains.iiasa.ac.at) is the central tool used in the analysis. GAINS, developed by the IIASA, brings together data on economic development, the structure, control potential and costs of emission sources, the formation and dispersion of pollutants in the atmosphere and an assessment of environmental impacts of pollution (http://gains.iiasa.ac.at). It is used here to estimate emissions of $PM_{2.5}$ and its precursor pollutants, to calculate ambient $PM_{2.5}$ concentrations arising from the emissions, as described further in Section 1.2, and to evaluate the health impacts as detailed below.

From ambient $PM_{2.5}$ concentrations, health impacts in terms of mortality and morbidity are calculated. All outcomes are listed in Box 1. GAINS routinely quantifies health impacts in terms of premature deaths ad YLLs from six diseases in line with the methodology developed within the GBD assessments (Murray et al., 2020). Within this assessment, impact calculations have been extended to cover morbidity related to cardiovascular and pulmonary diseases. For this purpose, new concentration-response relationships for several morbidity endpoints have been developed and are currently under review in the scientific literature. A full list of endpoints for mortality and morbidity covered by the assessment is given in Box 1 and a description of the CRFs is given in Section 1.4.

For each health outcome d (disease-specific mortality or morbidity), we calculate a population attributable fraction of the total burden based on the population exposure distribution to $PM_{2.5}$,

$$PAF_{da} = \frac{\sum_n pop_n \cdot (RR_{nda} - 1)}{\sum_{n'} pop_{n'} \cdot RR_{n'da}} \qquad 1$$

where RR_{nda} is the relative risk for annual mean $PM_{2.5}$ concentration level n, to which pop_n people are exposed. *RR* and thus also *PAF* can be specific to age a; for disease endpoints where the CRF are not age specific, the index a can be dropped from Eq. 1.

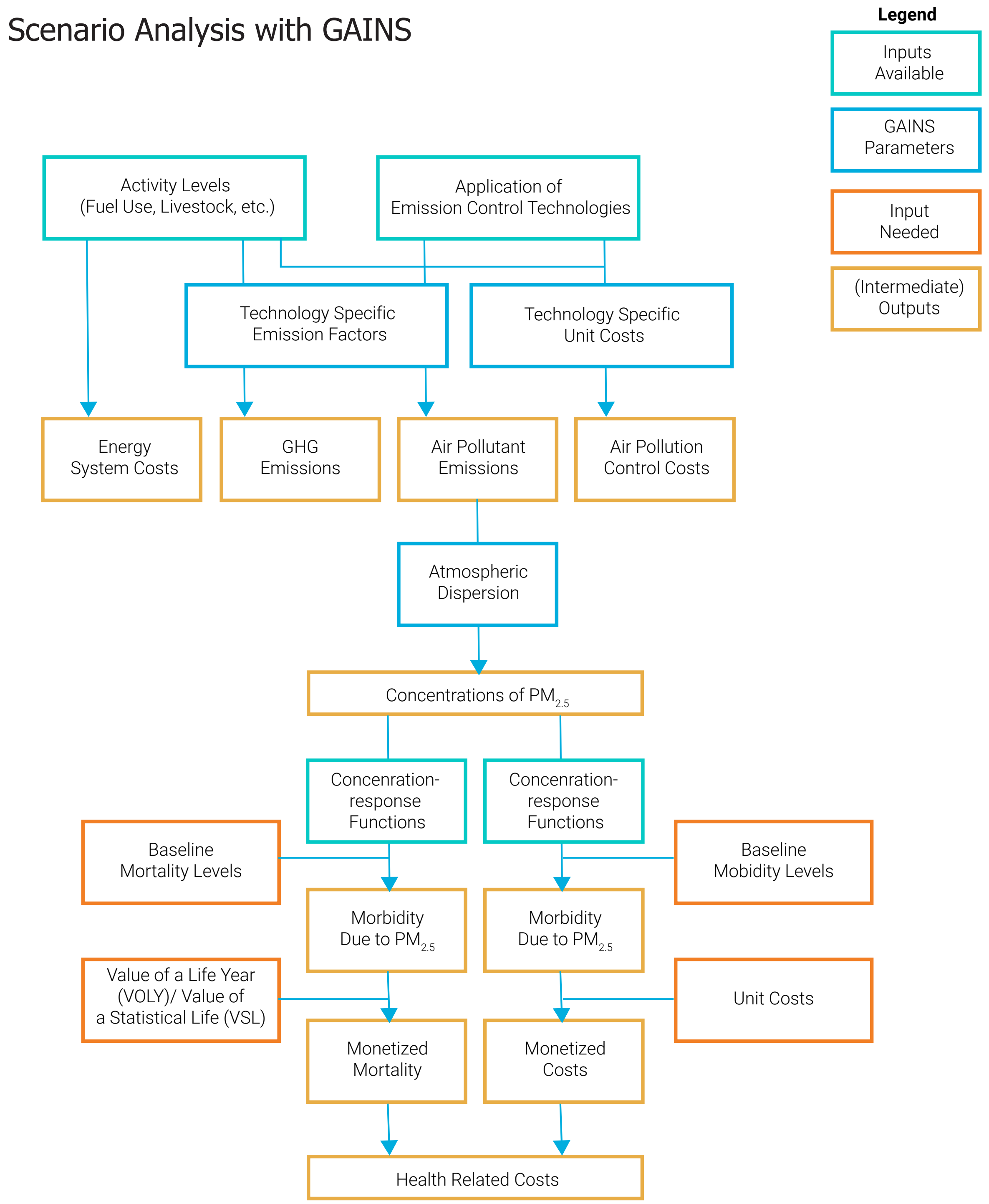

Fig 1. *Flow of information in the GAINS model to assess policy costs and impact related costs for one scenario (Current Policies or Mitigation cases). Orange fields highlight data inputs needed from local partners*

Attributable cases c of death, hospitalization, emergency room visits or restricted activity days are calculated as

$$c_{da} = PAF_{da} \cdot c_{BL,da} \qquad 2$$

where $c_{BL,da}$ are the baseline number of cases for the specific outcome d. The calculation is age specific for mortality. Baseline mortality rates in five year age groups were taken from the GBD Results Tool, representing the GBD results for 2019 (Murray et al., 2020). Baseline morbidity rates have been derived from internationally available data sets and national inputs, as described in Section 1.5. We assume that incidence rates stay constant in the future. Population projections follow the UN World Population Prospects 2017 (UN, 2017).

Box 1: Endpoints considered in the assessment.

Causes of death considered in the assessment:

- Chronic obstructive pulmonary disease
- Ischemic heart disease
- Stroke
- Lung cancer
- Acute lower respiratory infections
- Type 2 diabetes

Morbidity indicators considered in the assessment:

- Asthma-related emergency room visits
- Cardiovascular hospital admissions (pre/post 65 years)
- Respiratory hospital admissions
- Respiratory restricted activity days (working age)

From premature deaths, YLLs are calculated by multiplying the number of attributable deaths with the remaining life expectancy at the age of death. We note that this approach is conservative in the sense that it relies on the actual life table for the country itself. Other approaches, such as the GBD assessments, use remaining life expectancy from countries with the highest observed life expectancies for this purpose, such as Japan, and therefore arrive at higher estimates of YLLs.

The calculation of impact related costs relies on unit costs uc_d for each outcome d which are multiplied with the $PM_{2.5}$ attributable number c_d for each outcome:

$$cost_d = c_d \cdot uc_d \qquad 3$$

For the valuation of mortality, either the VSL or the VOLY can be used. VSL needs to be combined with the number of attributable deaths, while VOLY is used in conjunction with the number of YLLs. Cost data used in the assessment rely on a combination of national inputs and default estimates from international data sets, as described in Section 1.6.

The quantification of health impacts and impact costs by measure relies on the definition of mitigation measures as described in the main report, Table 1. While the GAINS model uses linear relationships between emissions and $PM_{2.5}$ concentrations, the risk functions for mortality are non-linear, which would imply that the size of the effect of a measure depends on the sequence of the measures taken. In order to avoid this complication, we linearize the relationship between $PM_{2.5}$ concentrations and each health outcome based on the concentration and health impact levels attained under the Current Policies scenario and the Strong Mitigation case.

Emissions and ambient $PM_{2.5}$ concentrations

GAINS uses activity projections from external sources (for example, macroeconomic projections and energy production and use from IEA world energy model (IEA, 2019), projections of livestock and fertilizer use from the UN Food and Agriculture Organization (e.g., Alexandratos and Bruinsma (2012)) as drivers and combines them with information on application rates of a large portfolio of emission control measures to calculate emissions of air pollutants (all key precursors of $PM_{2.5}$, including primary $PM_{2.5}$, SO_2, NO_x, NH_3, NMVOC) and GHGs. Each technology is associated with an emission factor for each pollutant, and cost characteristics used to quantify costs of air pollution abatement measures.

Emissions are calculated at a detailed sectoral level based on activity data, uncontrolled emission factors, the removal efficiency of emission control technologies and the extent to which such technologies (measures) are applied:

$$E_{i,p} = \sum_k \sum_m A_{i,k} ef_{i,k,m,p} \, x_{i,k,m,p} \qquad 4$$

where:

i, k, m, p	Source region, activity type, abatement measure, pollutant, respectively
$E_{i,p}$	Emissions of pollutant *p* (for SO_2, NO_x, NMVOC, NH_3, $PM_{2.5}$) in source region i. Emissions of GHGs (CO_2, CH_4, N_2O) are also calculated.
$A_{i,k}$	Activity level of type *k* (e.g., coal consumption in power plants) in source region *i*
$ef_{i,k,m,p}$	Emission factor of pollutant *p* for activity *k* in region *i* after application of control measure *m*
$x_{i,k,m,p}$	Share of total activity of type *k* in region *i* to which a control measure *m* for pollutant *p* is applied.

In terms of source regions, GAINS has global coverage with source regions which are countries or sub-national units in most parts of Asia. Cambodia is represented as one source region at national level.

To calculate ambient $PM_{2.5}$ concentrations, GAINS uses a linear approximation of the EMEP Chemistry Transport Model (Simpson et al., 2012) as described in the Supplementary Information to (Amann et al., 2020). $PM_{2.5}$ concentrations are calculated on a 0.1° grid (roughly 10x10km) and thus correspond to urban background levels, not to pollution hotspots.

Validation of ambient $PM_{2.5}$ concentrations

Fig. 2 shows a comparison of modelled $PM_{2.5}$ concentrations for 2015 against monitoring data for recent year provided by the Ministry of Environment and the US Embassy stations in Jakarta. Only stations with temporal coverage >75% are used in the comparison. GAINS reproduces the variation of concentrations well but overestimates total $PM_{2.5}$ in the more polluted regions in Western Java like Bandung; also Jakarta seems somewhat overestimated. This may be due to problems in the geographic distribution of emission sources in the GAINS model.

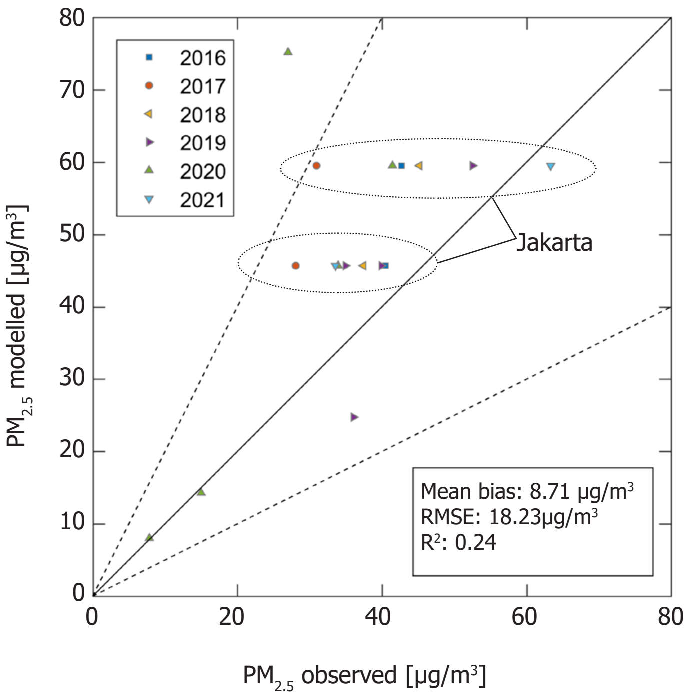

Fig 2. *2 Comparison of $PM_{2.5}$ concentrations modelled with GAINS for 2015 against observations from 2016 to 2021*

Concentration-response functions (CRFs)

CRFs used in this project have been derived from a meta-analysis of recent epidemiological studies going beyond the evidence available to earlier assessments. Endpoints were selected based on the CarbonH tool (Spadaro et al., 2018).

The full documentation is currently under review (Ru et al., in review). Outcomes are:

- Asthma-related emergency room visits
- Cardiovascular hospital admissions (pre/post 65 years)
- Respiratory hospital admissions
- Respiratory restricted activity days (working age)

In addition to these endpoints, CRFs for asthma related hospital admissions, bronchitis incidence in children, and incidence of dementia have been developed by Ru et al. (in review) but these are not used in the current assessment.

Ru et al. (in review) developed two versions of the CRF using either a log-linear or a nonlinear regression model to fit the available studies. In this assessment, we use the log-linear version. Since the quantification of benefits from individual measures requires a linearization step, the log-linear CRFs seem better suited.

In the log-linear CRFs, relative risk is expressed as,

$$RR\ (PM) = \exp\ (\beta \cdot PM)$$

With the coefficient β derived from the regression analysis as

Asthma-related emergency room visits	0.0034/μg/m^3
Cardiovascular hospital admissions (pre 65 years)	0.0009/μg/m^3
Cardiovascular hospital admissions (post 65 years)	0.0013/μg/m^3
Respiratory hospital admissions	0.0013/μg/m^3
Respiratory restricted activity days (working age)	0.0102/μg/m^3

Although the CRFs are for outcomes which typically relate to impacts of short-term exposure to $PM_{2.5}$, they are applied here to the annual mean concentrations. Ru et al. compared the effects of using annual means versus the time series in the United States and found a small overestimation of 0.1% to 1.3% depending on the morbidity outcome, which is not taken into account in this analysis in view of many other – likely much larger – uncertainties.

Baseline Morbidity Rates

The robustness of the results of the assessment crucially depends on baseline rates for mortality and morbidity incidences. While cause specific mortality estimates by age group are available from the GBD Results Tool (https://vizhub.healthdata.org/gbd-results/) consistent with the GBD 2019 assessment (Vos et al., 2020), baseline rates for the morbidity endpoints considered here were only partially available from national data (Section 1.5.1). For those endpoints where national data were not available, default rates have been estimated from international datasets as described in Section 1.5.2.

National data

Data on hospital admissions by illness in 2019-2021 have been made available to this assessment by the Ministry of Health. These have been used to calibrate the baseline morbidity levels in the assessment for the outcomes related to cardiovascular and respiratory hospital admissions. We used only 2019 data in order to avoid possible temporary effects during the Covid-19 pandemic.

Asthma related emergency room visits were estimated based on the asthma hospital admission rate, scaled with the ratio of asthma related ERVs to hospital admissions in the default data set.

Baseline rates of the related diseases: Default estimates

Data on baseline morbidity rates are often difficult to obtain, which is why a default data set was estimated from global sources. The morbidity endpoints considered here, such as hospital admissions and emergency room visits, are the combined outcomes of the prevalence of the diseases and some other factors. These factors influence whether people with the disease get admitted to a hospital, or whether they go to the emergency room. As such, we derive the country-specific baseline morbidity data based on the baseline prevalence rates of the respective diseases of the country and then adjust with the benchmark baseline rates reported in available sources.

We obtained the baseline prevalence rate of the related diseases from the GBD 2019 (Global Burden of Disease Collaborative Network, 2021) with the following mapping:

Morbidity endpoints	Related diseases in GBD 2019
Asthma emergency room visit (ERV) for all population	Prevalence rate of asthma (>=20)
Asthma hospital admission for post-20	Prevalence rate of asthma (>=20)
Asthma hospital admission for below-20	Prevalence rate of asthma (<20)
Cardiovascular hospital admission for below-65	Prevalence rate of cardiovascular diseases (<70)
Cardiovascular hospital admission for post-65	Prevalence rate of cardiovascular diseases (>=70)
Respiratory hospital admission for all-age population	Prevalence rate of chronic respiratory diseases, all age

Country-specific data was obtained for the year 2015 for both genders from the GBD Results Tool (https://vizhub.healthdata.org/gbd-results/).

Direct statistics of the respective morbidity endpoints were obtained for the United States from the Agency for Healthcare Research and Quality's HCUPnet Online Database (Agency for Healthcare Research and Quality [AHRQ], 2022) (https://hcupnet.ahrq.gov/) as benchmark data. We then calculated a scaling factor between the related diseases and the morbidity cases and applied to the country. By doing this, we understand that our results are based on a strong assumption that the relationship between morbidity outcomes and the related diseases causing the outcomes are the same universal and same with the relationship derived in the US. We realize that other countries may have different availabilities for hospital admissions and emergency rooms, especially in rural areas.

Unit Costs

As with the baseline morbidity data, the unit costs used in this study (see main report, Table 2) are informed in parts by national data (Section 1.6.1) and complemented by default estimates from international data for all outcomes where national data were not available (Section 1.6.2).

National data

Unit costs for hospital admissions for cardiovascular and respiratory diseases were provided by the Indonesian Ministry of Health, alongside with a preferred estimate for the value of a statistical life in Indonesia relating to (Robinson et al., 2019). The value of a life year used in the analysis was adjusted by the ratio of the VSL in this estimate over the VSL in our default data set. All costs provided for years other than 2015 were inflation-adjusted to 2015.

Default estimates from international data

Unit costs for each morbidity outcome were estimated from international data sets. Specifically, we obtained unit cost data for 54 countries from the CaRBonH tool (Spadaro et al., 2018). Most of these countries were in Europe and Central Asia. We also obtained the unit cost data from HCUPNet (AHRQ, 2022). As such, we had a unit cost dataset from 55 countries. We then obtained the GDP per capita data from the World Data Bank (World Bank, 2021). We ran regressions for the unit cost of each endpoint using the logarithm of GDP per capita:

$$\ln\left(Unit\ cost_{ij}\right) = \beta_{0i}\ln(\text{GDP per capita}_j + \beta_{1i})$$

where i indicates different morbidity endpoints, and j indicates different countries. The coefficients we obtained from the regressions were as below:

Endpoint	Intercept	Slope
Children asthma symptom day	6.06	0.65
Restricted activity day	6.84	0.65
Hospital admission	10.81	0.78
VSL	17.09	0.65
VOLY	13.82	0.65

We used the regression coefficients to estimate unit costs for other countries for each endpoint. The estimated cost is per case of the morbidity.

Annex 2. Emission scenarios

Both developed scenarios (Current Policies and Strong Mitigation) draw on the socio-economic assumptions in the World Energy Outlook 2018 scenarios (IEA, 2018). The macroeconomic outlook for the ASEAN region in that study forecasted a robust growth of the respective economies. The scenarios differ, i.a., with respect to considered energy and agriculture sector efficiency improvements and assumptions about the implementation of air pollution control technologies/ policies, which has implications on emissions of air pollutants as well as GHGs as is illustrated in the following sections and in the national assessment.

Current Policies

As a result of the continued strong economic growth, the modelling anticipates significant increase of CO_2 emissions for the 2030 in the Current Policies scenario, which represents a baseline in this assessment: nearly 60% increase from 2015. The main contributions and growth of CO_2 emissions in the ASEAN region are from power, industry, and transport sectors (Fig. 3). The scenario draws from the World Energy Outlooks New Policy Scenario and includes NDCs reported up to 2018 (IEA, 2018).

The baseline (Current Policies) also assumes that existing and recently introduced legislation in the power, industry and transport sectors (e.g., Zhang (2016); Motokura et al. (2017); He et al. (2021); Dieselnet.com (n.d.); TransportPolicy.net (n.d.)) are implemented effectively, and have slowed the growth of emissions of key PM precursors. In fact, emissions of these precursors are growing slower than CO_2, suggesting gradual decoupling of economic growth from air pollutant emissions. At the same time, however, the existing legislation is not sufficiently strong to offset the increase in fuel use and production activities, which explains the relatively faster growth in CO_2 (Fig. 3).

Another notable trend involves residential cooking, a sector that contributes a significant share of primary $PM_{2.5}$. For primary $PM_{2.5}$ emissions, a trend towards clean fuels for cooking is clearly seen through declining emission in this subsector (Fig. 3); affecting also trend for NMVOC. This is the result of the long-standing policies to provide access to clean energy both for rural and urban residents in the region.

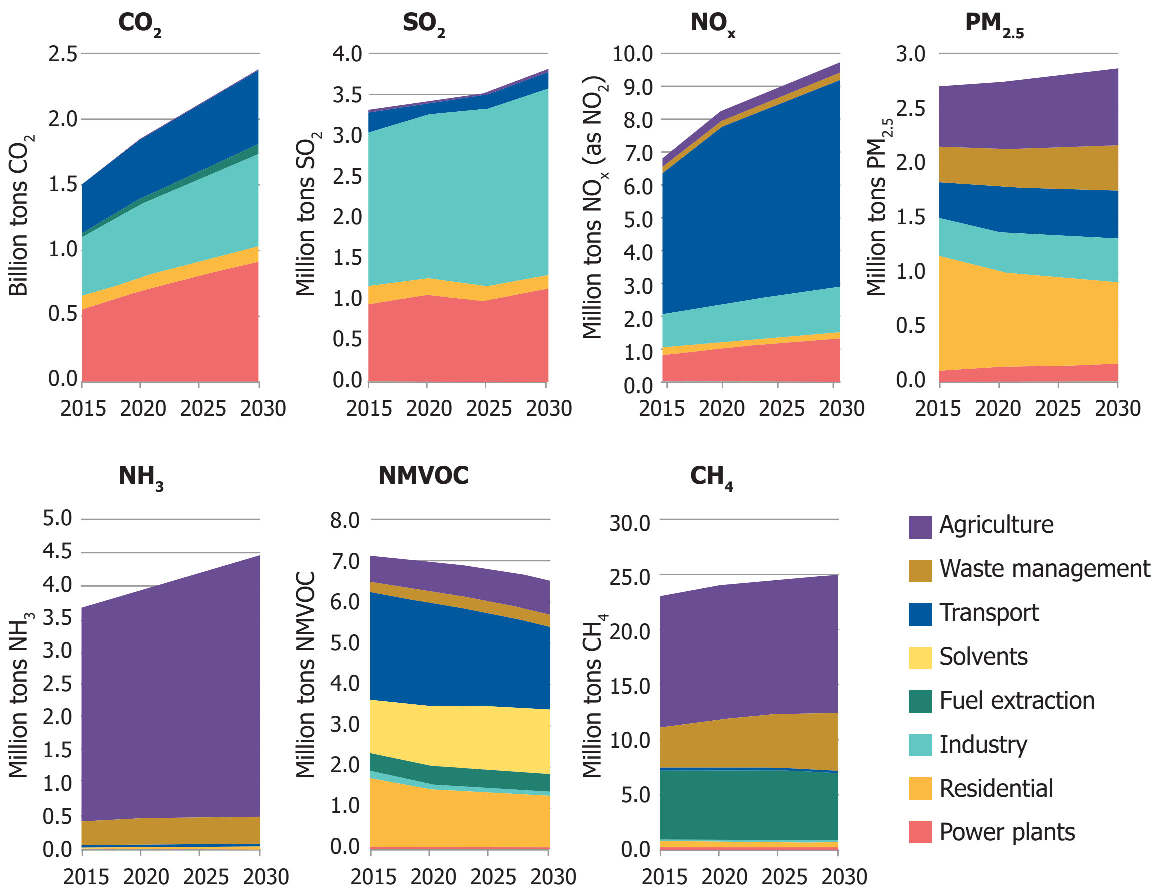

Fig 3. *Sectoral emissions of CO_2, primary $PM_{2.5}$, key precursors of ambient $PM_{2.5}$, and CH_4 for the ASEAN region in the Current Policies scenario*

Strong Mitigation

This scenario identifies further reduction potential by 2030 (beyond Current Policies) considering application of technologies with lowest emissions included in the GAINS model database, assuming their full and effective application while considering the limits of technical feasibility, and impact of selected non-technical measures. The 'non-technical measures' refer to measures that explore the potential for: further improvements in energy efficiency in different sectors, increasing the share of electric vehicles, accelerating access to clean energy for cooking, achieving significant improvements in nitrogen use efficiency in agriculture, and dietary changes (e.g., lower meat protein consumption) assuming that calorific intake is in line with the Lancet EAT Planetary Diet (Willett et al., 2019).

The potential for energy efficiency, fuel switching, electric vehicles originate from the assessment and comparison of the IEA, NPS and the SDS where the latter is designed to achieve CO_2 reduction consistent with the Paris Agreement targets (IEA, 2018).

While the policies implemented in the Current Policies contribute to the slower growth in air pollution (Fig. 3), comparing Strong Mitigation scenario with the Current Policies shows significant opportunities to reduce emissions further (Fig. 4).

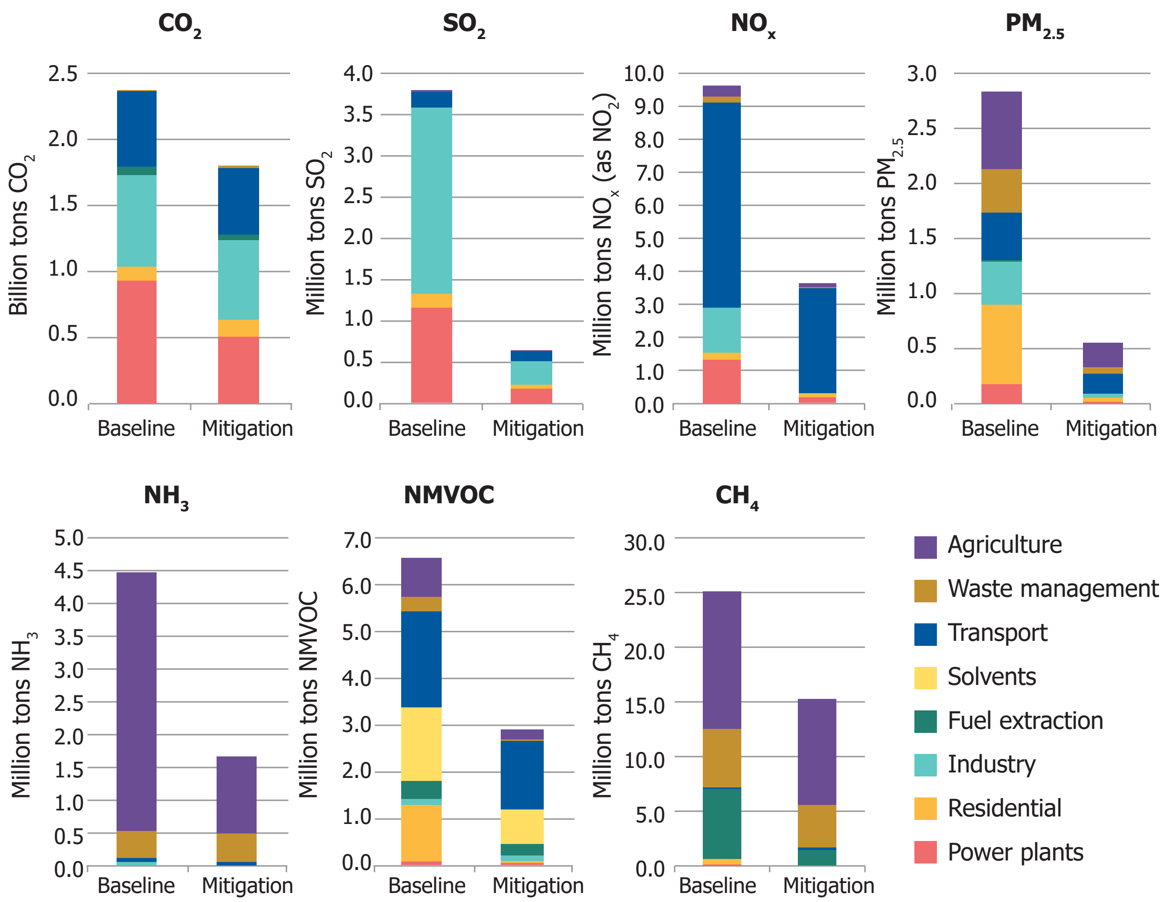

Fig 4. *Sectoral emissions of CO_2, primary $PM_{2.5}$, key precursors of ambient $PM_{2.5}$, and CH_4 for the ASEAN region in the Current Policies (Baseline) and Strong Mitigation scenario estimated for 2030*

While CO_2 emissions decline by nearly 25% considering efforts to increase energy efficiency and fuel switching potential, the air pollutant emissions are estimated to decline by from 55% (NMVOC) to 84% (SO2), and emissions of CH_4 decline by 40%. Achieving such reductions would require additional policy action stimulating introduction of further measures which were developed for the Strong Mitigation case. They include 12 measure packages; each package includes several technologies applicable to the particular sector(s). More detailed discussion of how the measures were derived are included in the UNEP/CCAC (2023)[7] and also UNEP (2019) reports.

[7] That report identified 15 solutions which included measures targeting reduction of CH_4 and hydrofluorocarbons (HFCs), i.e., rice paddies, wastewater treatment, and HFC-refrigerant replacement.

Individual Measures

Table 1 provides description of the 12 measure packages that bring significant reduction of air pollutant emissions in the ASEAN region. The measures represent bundles of policies rather than individual actions and have been selected based on their potential to deliver the maximum reduction in population's exposure to $PM_{2.5}$.

As shown in the national assessment report, several of these measures also bring strong co-benefits including reduction of GHGs emissions and contribute to the achievement of several SDGs.

Table 1. *Description of key mitigation options associated with the identified 12 solutions*

12 solutions	Brief description
Clean cooking	Clean alternatives for traditional cooking including Liquefied Petroleum Gas (LPG) stoves and higher efficiency solid fuel stoves incl. fan assisted stoves.
Renewables, post-combustion controls in power and industry	Consideration of potential for fuel switch and renewable energy and application of high efficiency flue gas cleaning technology in power plants and industrial boilers, including flue gas desulfurization, high efficiency dust removal.
Industrial Process standards, incl. energy efficiency	Improvements in process technology, more efficient capture and removal of process and fugitive emissions from industrial production.
Emission standards/ electrification - transport	Introduction of more stringent emission limit values and energy efficiency standards for vehicles. Further potential is estimated assuming the immediate introduction of legislation requiring for new vehicles (road and non-road) the Euro VI/6 equivalent emission standards and/or accelerated electrification of fleet.
Vehicle inspection and maintenance	Introduction of stricter legislation requiring more frequent and enforced vehicle inspection and maintenance that will enable early recognition and elimination/repair of high emitting vehicles.
International shipping	Low sulfur fuel, i.e., 0.5%S in heavy fuel oil with further reduction to 0.1%S, introduction of particulate filters and NO_x Reduction Selective Catalyst Reduction (deNOx SCR) installations. Alternatively, flue gas desulfurization can be installed to achieve the same reduction of SO_2 as when using low sulfur fuel.
Livestock and N fertilizer application	Control of NH_3 emissions from livestock production and mineral nitrogen fertilizers application. Livestock measures include construction of new low emission housing, covered stores for manures, and efficient application of manures on land. For mineral fertilizers, emissions from urea application are addressed either by replacing urea with, for example, ammonium nitrate, improving urea application (proper timing and doses), and promotion of new formulations and urease inhibitors.
Dietary changes	Shift to less meat protein in diets resulting in lower numbers of livestock and lower mineral fertilizer use as well as improved nitrogen use efficiency.
Agriculture residue burning	Efficient enforcement or banning the open burning of agricultural residues.
Waste management	Primarily addressing solid municipal waste management by reducing trash burning and introducing efficient waste collection and recycling schemes.
Prevention of forest, peatland fires	Improved forest, land and water management and fire prevention strategies. Enhance collaboration through ASEAN Agreement on Transbounday Haze Pollution.
Coal, oil and gas production and distribution	While most of the measures in fossil fuel extraction, processing, and distribution would reduce emissions of CH_4, there are some reductions of PM precursors (including BC) when routine flaring is reduced or banned as well as reducing tailing fugitive dust emissions from mining industry following reduced demand for coal in SDSs.

REFERENCES

Acid Deposition Monitoring Network in East Asia. (2020). *Policies and Practices Concerning Acid Deposition – Indonesia.* EANET. https://www.eanet.asia/wp-content/uploads/2020/04/3-Indonesia_Factsheet_compressed.pdf

Agency for Healthcare Research and Quality. (2022). *Healthcare Cost and Utilization Project (HCUPnet) Data Tools.* AHRQ. https://datatools.ahrq.gov/hcupnet#setup

Alexandratos, N., & Bruinsma, J. (2012). World agriculture towards 2030/2050: The 2012 revision. *ESA Working paper Rome, FAO.*

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L. et al. (2011). Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications, *Environmental Modelling & Software,* 26 (12), 1489–1501, https://doi.org/10.1016/j.envsoft.2011.07.012

Amann, M., Jiming, H., Borken-Kleefeld, J., Cofala, J., Sanabria, A. G., Heyes, C. et al. (2019). *Scenarios and Solutions, in: Air Pollution in Asia and the Pacific: Science-based solutions.* United Nations Environment Programme (UNEP), Bangkok, Thailand, 61–100.

Amann M, Kiesewetter G, Schoepp W, Klimont, Z., Winimarter, W., Cofala, J. et al. (2020). Reducing global air pollution: The scope for further policy interventions. *Philosophical Transactions of the Royal Society a Mathematical, Physical and Engineering Sciences.* https://doi.org/10.1098/rsta.2019.0331

DieselNet. (n.d.). *Emissions Standards.* https://dieselnet.com/standards/

Global Burden of Disease Collaborative Network. (2021). *Global Burden of Disease Study 2019 (GBD 2019).* Seattle, United States of America: Institute for Health Metrics and Evaluation (IHME).

Greenstone, M., & Fan, Q. (Claire). (2019). Indonesia's Worsening Air Quality and its Impact on Life Expectancy, Energy Policy Institute at the University of Chicago (EPIC). https://aqli.epic.uchicago.edu/wp-content/uploads/2019/03/Indonesia-Report.pdf

Haines, A., Amann, M., Borgford-Parnell, N., Leonard, S., Kuylenstierna, J., & Shindell, D. (2017). Short-lived climate pollutant mitigation and the sustainable development goals. *Nature Climate Change*, 7, 863–869. https://doi.org/10.1038/s41558-017-0012-x

He, X., Shen, W., Wallington, T. J., Zhang, S., Wu, X., Bao, Z. et al. (2021). Asia Pacific road transportation emissions, 1900–2050. *Faraday Discussions, 226.*

Health Effects Institute. (2020). *State of Global Air 2020. Special Report.* Boston, MA: Health Effects Institute.

International Energy Agency. (2019). World Energy Model Documentation - 2019 version. Paris, France.

Lestari, P., Arrohman, M. K., Damayanti, S., & Klimont, Z. (2022). Emissions and spatial distribution of air pollutants from anthropogenic sources in Jakarta. *Atmospheric Pollution Research,* 13, 101521. https://doi.org/10.1016/j.apr.2022.101521

Motokura, M., Lee, J., Kutani, I., & Phoumin, H. (2017). *Improving Emissions Regulations for Coal-Fired Power Plants in ASEAN*. ERIA Research Project Report, Jakarta.

Murray, C.J.L., Aravkin, A.Y., Zheng, P., Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M. et al (2020). Global burden of 87 risk factors in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet,* 396(10258), 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2

Organization for Economic Co-operation and Development. (2019). *Green Growth Policy Review of Indonesia 2019.* OECD. https://www.oecd.org/env/oecd-green-growth-policy-review-of-indonesia-2019-1eee39bc-en.htm

Robinson, L.A., Hammitt, J.K., & O'Keeffe, L. (2019). Valuing Mortality Risk Reductions in Global Benefit-Cost Analysis. *Journal of Benefit-Cost Analysis,* 10,15–50. https://doi.org/10.1017/bca.2018.26

M. Ru, D. Shindell, J.V. Spadaro, J-F. Lamarque, A. Challapalli, F. Wagner, G. Kiesewetter, New concentration-response functions for seven morbidity endpoints associated with short-term PM2.5 exposure and their implications for health impact assessment, *Environment International* (2023), doi: https://doi.org/10.1016/j.envint.2023.108122

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H. et al. (2012) The EMEP MSC-W chemical transport model–technical description. *Atmospheric Chemistry and Physics,* 12,7825–7865.

Spadaro, J.V., Kendrovski, V., & Martinez, G.S. (2018). *Achieving health benefits from carbon reductions: Manual for CaRBonH calculation tool.* WHO Regional Office for Europe, Denmark

TransportPolicy.net. (n.d.). *Indonesia: Fuels: Diesel and Gasoline.* https://www.transportpolicy.net/standard/indonesia-fuels-diesel-and-gasoline/

United Nations. (2017). *World Population Prospects: The 2017 Revision.* United Nations Department of Economic and Social Affairs. UN. https://www.un.org/development/desa/publications/world-population-prospects-the-2017-revision

United Nations Environment Programme. (2015). *Air Quality Policies in Indonesia.* UNEP. https://www.unep.org/resources/policy-and-strategy/air-quality-policies-indonesia

United Nations Environment Programme. (2019). *Air Pollution in Asia and the Pacific: Science-Based Solutions.* UNEP, Nairobi, Kenya.

United Nations Environment Programme/Climate and Clean Air Coalition. (2023). *Clean Air and Climate Solutions for ASEAN.* UNEP/CCAC, Nairobi, Kenya.

Vos, T., Lim, S.S., Abbafati, C., Abbasi, M., Abbasifard, M., Abbasi-Kangevari, M. et al. (2020). Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, 396 (10258), 1204–1222. https://doi.org/10.1016/S0140-6736(20)30925-9

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S. et al. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

World Bank. (2021). *World Development Indicators 2021.* The World Bank. https://databank.worldbank.org/

Zhang, X. (2016). E*mission standards and control of* $PM_{2.5}$ *from coal power plant.* IEA Clean Coal Centre, London.

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