

# ASSESSMENT OF THE COST OF INACTION OF TACKLING AIR POLLUTION IN CAMBODIA





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# ACRONYMS

AHRQ	Agency for Healthcare Research and Quality
ASEAN	Association of Southeast Asian Nations
BC	Black Carbon
CH <sub>4</sub>	Methane
CO <sub>2</sub>	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 <sub>3</sub>	Ammonia
NMVOC	Non-methane Volatile Organic Compound
NO <sub>x</sub>	Nitrogen Oxides
NO <sub>2</sub>	Nitrogen Dioxide
NPS	New Policy Scenario
O <sub>3</sub>	Ozone
OC	Organic Carbon
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SDGs	Sustainable Development Goals
SDS	Sustainable Development Scenario
SLCPs	Short Lived Climate Pollutants
SO <sub>2</sub>	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 Cambodia. It quantifies and compares the potential health costs in two alternative scenarios, one in which no further measures beyond current policy are taken, with a future scenario in which 12 solutions (bundles of measures) are implemented. 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:

**Cambodia 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 Cambodia. 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 almost 5 thousand premature deaths due to ambient air pollution exposure in Cambodia per year by 2030.

**Further action could have significant health benefits for the population of Cambodia.** Implementing further policies beyond current legislation could avoid over 3 thousand premature deaths, 5 thousand hospital admissions and 1.5 thousand emergency room visits due to poor air quality every year by 2030.

**The human health related costs of not taking further action on air pollution are estimated to be equal to about 2.1% of Cambodia's Gross Domestic Product (GDP) in 2030.** Lack of immediate further action on air pollution could cost Cambodia nearly 800 million USD a year in 2030, based on a selection of mortality and morbidity impacts of air pollution. This equals about 2.1% of Cambodia'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 Cambodia include a complete switch to clean cooking technologies, policies supporting accelerated introduction of electric vehicles and strengthened emission standards for road transport, effective waste management strategies, enforcement of bans on agricultural residue burning, and improved management preventing forest and peatland fires. These measures alone would capture about 80% of the mitigation potential in terms of exposure and monetized benefits.

**The proposed 12 solutions also result in significant reduction of greenhouse gas (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 Cambodia 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 (SDGs). 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 Cambodian 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. Cambodia is not exempt from this burden; exposure to ambient fine particulate matter (PM<sub>2.5</sub>) was estimated to cause about 3,500 (1,800-5,700) premature deaths annually in Cambodia in 2019 (Murray et al., 2020). Furthermore, exposure to PM<sub>2.5</sub> is responsible for a high burden of morbidity from cardiovascular and respiratory diseases, and air pollution also affects ecosystems through deposition of nitrogen and sulfur, leading to acidification, eutrophication, and loss of biodiversity.

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. In Cambodia, multiple strategies and action plans have been developed which either directly or indirectly target emissions of air pollutants across multiple sectors. These include sector specific strategies relating to energy efficiency improvements, increased renewable energy capacity, reducing agricultural burning, more sustainable transport, improved waste management as well as legislation defining air pollutants' emission limit values for industrial stationary combustion and production facilities (Zhang, 2016; Motokura et al., 2017; Acid Deposition Monitoring Network in East Asia [EANET], 2020; Ministry of Environment, 2021), and transport sources (He et al., 2021). However, even if these 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 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 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<sub>2.5</sub>. In fact, full implementation of these solutions can reduce population weighted PM<sub>2.5</sub> 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

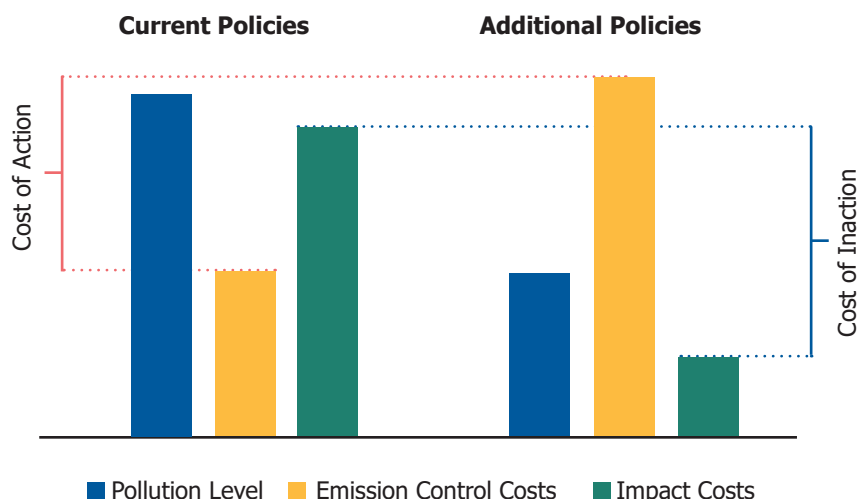
Through quantifying the costs of not acting on air pollution, this assessment aims to increase the evidence base to support policymakers and decision makers in Cambodia to take further action and prioritize ambitious policies and cost-effective measures to improve air quality. It provides an initial quantification of some of the costs of inaction from tackling air pollution in Cambodia, 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 Cambodia 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 GHG emissions, 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., 2011a; 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<sub>2.5</sub> 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<sub>2.5</sub>. 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 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; that should read 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 (SO<sub>2</sub>, NO<sub>x</sub>, PM (including black carbon (BC) and

organic carbon (OC)), Non-methane Volatile Organic Compound (NMVOC), ammonia (NH<sub>3</sub>) and GHGs.

The model computes the atmospheric dispersion and formation of secondary pollutants for defined scenarios. This allows the quantification of PM<sub>2.5</sub> 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<sub>2.5</sub> in the population is calculated. Applying concentration-response (CRF) functions from the international literature, GAINS calculates premature mortality from long-term exposure to PM<sub>2.5</sub> and the associated years of life 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 Cambodia will experience significant economic development in the future with its GDP more than doubling by 2030 from 18 billion US\$ in 2015, following the projections made in the International Energy Agency (IEA)'s World Energy Outlook 2018 (IEA, 2018). The population of Cambodia is also assumed to change into the future, growing from 15.4 million in 2015 to 18.6 million in 2030 and 21.7 million in 2050, following the UN World Population Prospects 2017 (UN, 2017), Medium Scenario. At the same time, the Cambodian 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 Cambodia by mid-2020. The information about current policies, emission limit values and

standards is taken from Zhang (2016), Motokura et al. (2017), EANET (2020), He et al. (2021), and Clean Air Plan of Cambodia (Ministry of Environment, 2021). The energy trends used in the Current Policies scenario are consistent with the IEA 'New Policies' (NPS) scenario, and air pollution controls are implemented to the extent foreseen under current legislation, but no further action is taken.

In contrast to this, **the Strong Mitigation** scenario (additional policy scenario in above Fig. 1.1), assumes that the additional 12 key solutions<sup>1</sup> 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<sup>2</sup>) and have been selected based on their potential to deliver the maximum reduction in the population's exposure to PM<sub>2.5</sub>. 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<sub>2.5</sub> 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 GHG emissions and contribute to the achievement of several SDGs.

<sup>2</sup> The UNEP/CCAC Clean Air and Climate Solutions for ASEAN Report (UNEP/CCAC, 2023) investigates 15 solutions, some of which however do not directly influence air pollution levels. This study includes the 12 solutions relevant for PM<sub>2.5</sub> concentrations.

<sup>3</sup> 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

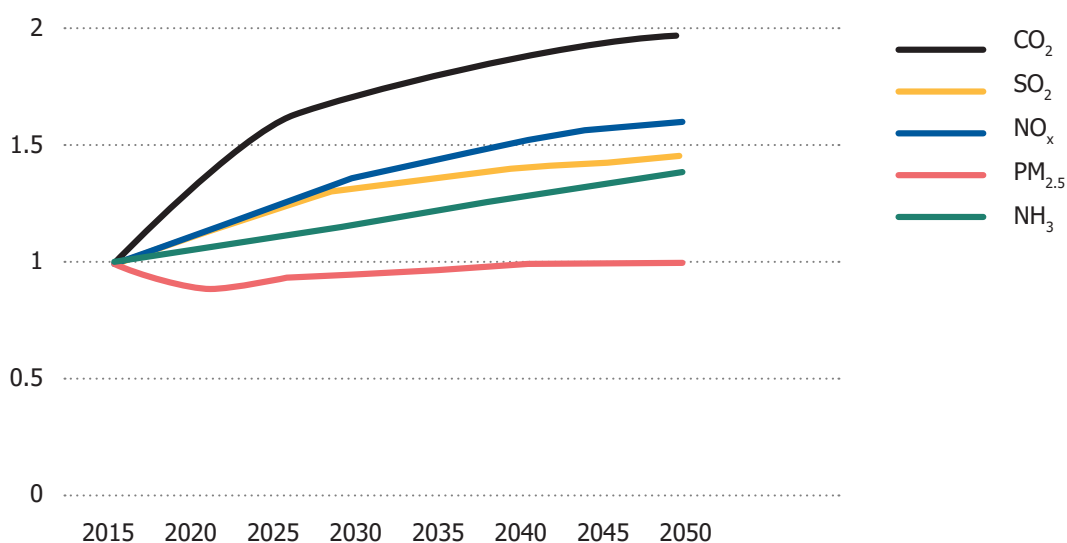
## 2. Results

This section presents results from the assessment itself. Section 2.1 quantifies the emissions and ambient PM<sub>2.5</sub> 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



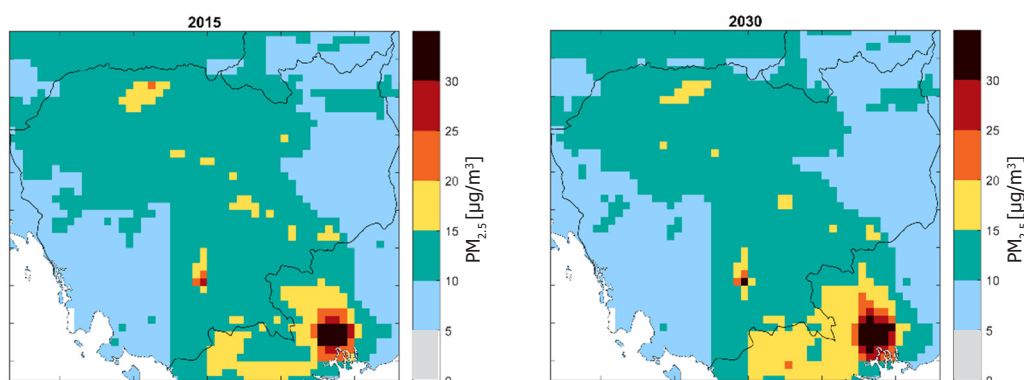
**Fig. 2.1** Trends in emissions of CO<sub>2</sub> and air pollutants in the Current Policies scenario for Cambodia

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<sub>2.5</sub> and key PM precursor pollutants (sulphur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), (Fig. 2.1). In fact, these precursors are growing slower than carbon dioxide (CO<sub>2</sub>), suggesting gradual decoupling of economic growth from air pollutant emissions. The main contributions and growth of CO<sub>2</sub> emissions in Cambodia are from transport, 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 Cambodia drives the significant increases in CO<sub>2</sub> emissions (Fig. 2.1). Another notable trend in the baseline involves the residential sector. For primary PM<sub>2.5</sub> emissions, cooking contributed over 50% of PM<sub>2.5</sub> in 2015, according to GAINS model estimates,

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 about 40% and 30% by 2030 and 2050, respectively, and contributing near stabilization of overall PM<sub>2.5</sub> emissions (Fig. 2.1).

Annual mean PM<sub>2.5</sub> concentrations in Cambodia estimated by GAINS for 2015 are between 5 and 30 µg/m<sup>3</sup> (Fig. 2.2, left panel). The highest modelled concentrations of PM<sub>2.5</sub> > 20 µg/m<sup>3</sup> are seen in Phnom Penh, in agreement with the observations from recent years (19-21 µg/m<sup>3</sup>). While this means that the PM<sub>2.5</sub> pollution problem in Cambodia is smaller than in many other Asian countries, concentrations are still considerably above the World Health Organization (WHO) guideline value of 5 µg/m<sup>3</sup>, particularly in cities.





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

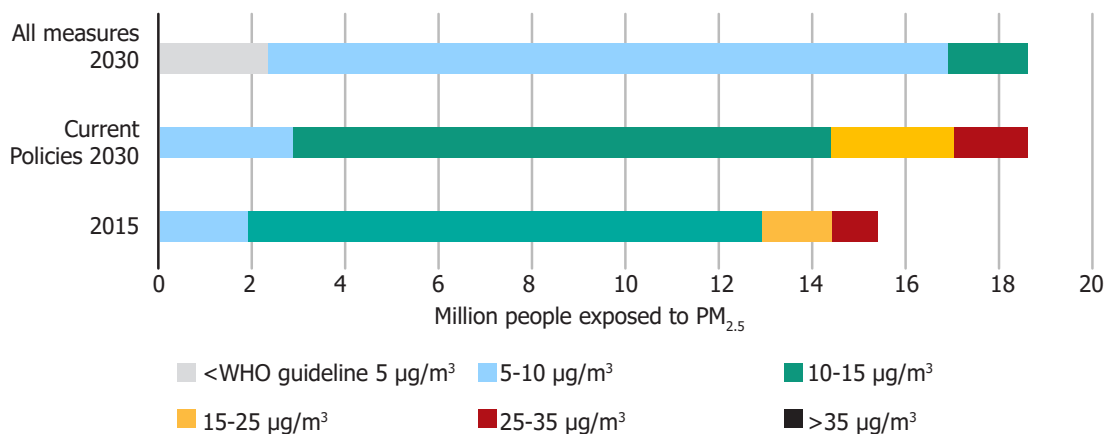
In 2015, the entire population of Cambodia are exposed to  $PM_{2.5}$  levels above the current WHO air quality guideline of  $5 \mu\text{g}/\text{m}^3$  and over 80% are exposed to levels above the 2005 WHO guideline of  $10 \mu\text{g}/\text{m}^3$ . In the Current Policies scenario, the situation is not expected to improve by 2030, even with assumed effective implementation of current legislation

85% of the population will still be exposed to  $PM_{2.5}$  concentrations above the 2005 WHO guidelines and the population exposed to concentrations exceeding  $15 \mu\text{g}/\text{m}^3$  would more than double from about 2 million to over 4 million owing to increasing concentrations in some regions (Fig 2.2 and Fig 2.3) as well as population growth and 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 2 million people would enjoy PM concentrations below the current WHO guidelines and less than 10%

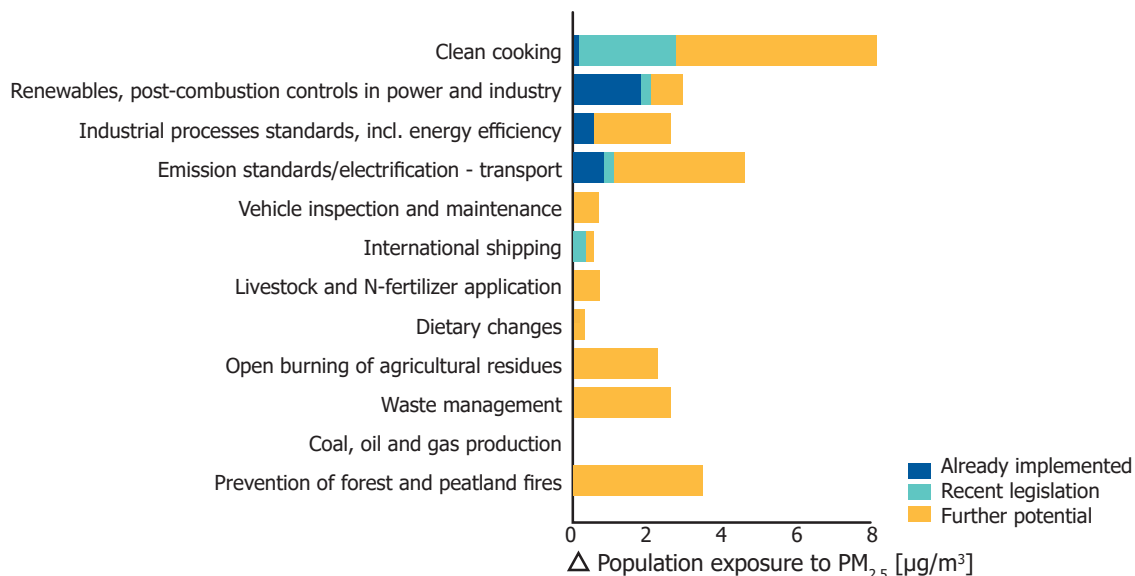
would be exposed to levels above  $10 \mu\text{g}/\text{m}^3$ . The Current Policies and the Strong Mitigation scenarios constitute the extreme ends of a spectrum of possible scenarios between business as usual and extremely ambitious mitigation. Within this range, a more realistic policy scenario would 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<sub>2.5</sub> 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<sub>2.5</sub> concentrations in Cambodia in 2030, assuming the full implementation of each solution both in Cambodia 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.

For example, if implemented, recent policies relating to the transition towards clean cooking will have some success in reducing air pollution (green bar) but there is also potential for further reductions through the implementation of more ambitious policies in this sector (yellow bar). 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.



**Fig. 2.4** Expected improvement in population-weighted mean PM<sub>2.5</sub> concentrations in Cambodia 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<sub>2.5</sub> leads to considerable health impacts in Cambodia. The GAINS model estimates that in 2015, more than 3,200 premature deaths were attributable to ambient PM<sub>2.5</sub>, corresponding to almost 70,000 YLLs. In the Current Policies scenario, due to increases in PM<sub>2.5</sub> concentrations, as well as population aging, the mortality burden is projected to increase to 4,700 premature deaths and 83,000 YLLs in 2030 under current legislation.

At the same time, PM<sub>2.5</sub> also contributes to a significant burden of morbidity. Numbers of morbidity and mortality attributable to PM<sub>2.5</sub> 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.

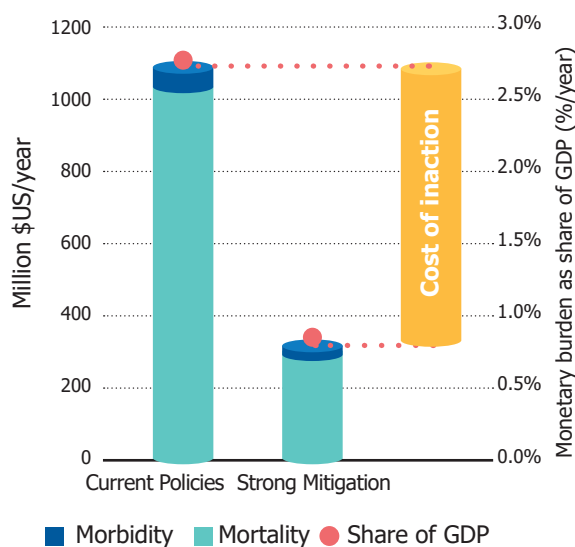
Unit costs, VSL and VOLY shown in Table 2 are taken from internationally available data sets and adapted to Cambodia's per-capita GDP (see Appendix 1 for details).

**Table 1.** Morbidity and mortality attributable to ambient PM<sub>2.5</sub> in Cambodia in 2015 and 2030 under current legislation and strong mitigation, 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		
<i>Mortality</i>							
Premature deaths	3,259	4,692	1,480	333,422	1,086,622	1,564,416	493,465
YLLs	69,537	82,648	26,123	12,608	876,750	1,042,053	329,364
<i>Morbidity</i>							
Asthma (Emergency Room Visits), all age	2,205	2,827	1,349	5	12	15	7
Cardiovascular hospital admissions, below 65 years of age	88	110	49	263	23	29	13
Cardiovascular hospital admissions, post 65 years of age	106	222	107	263	28	58	28
Respiratory hospital admissions, all age	5,703	7,302	3,520	263	1,501	1,922	926
Respiratory restricted activity days, working age	7,211,875	10,206,569	4,036,485	12	84,761	119,957	47,441

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 Cambodia are estimated to reach almost 1.2 billion USD per year, a value equal to 3.1% of Cambodia’s GDP. In contrast, in the Strong Mitigation scenario, due to the success of the 12 clean air solutions in reducing PM<sub>2.5</sub> concentrations, this cost is estimated to decrease to

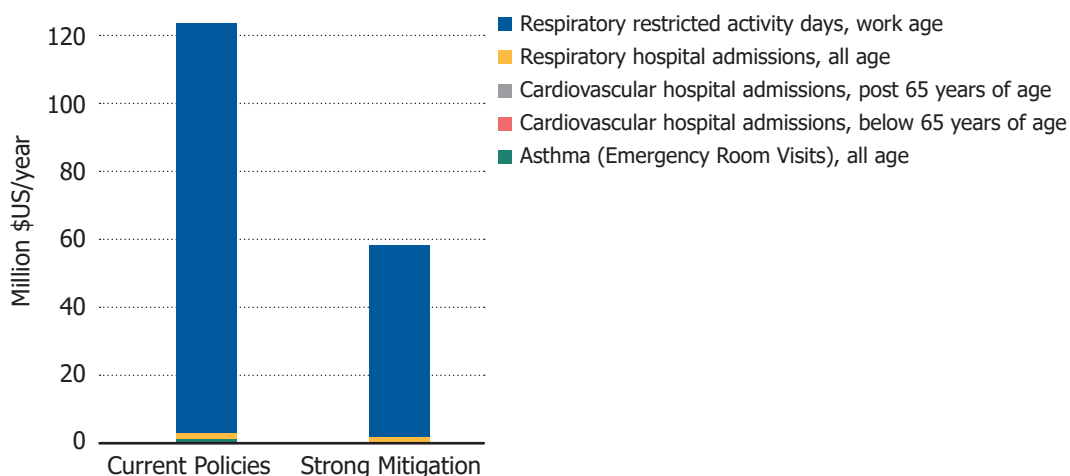
approximately 380 million USD per year, equivalent to about 1% of GDP in 2030. Therefore, this means that by not implementing the 12 clean air solutions and acting on air pollution, the cost of inaction in Cambodia is estimated to be almost 800 million USD per year, equivalent to around 2.1% of GDP in 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<sub>2.5</sub> exposure in 2030, comparing the Current Policies scenario, and effective implementation of all measures assessed in this study for Cambodia (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 consistently about 90% of costs.

The remaining 10% are dominated (98%) by costs associated with respiratory restricted activity days (Fig. 2.6).

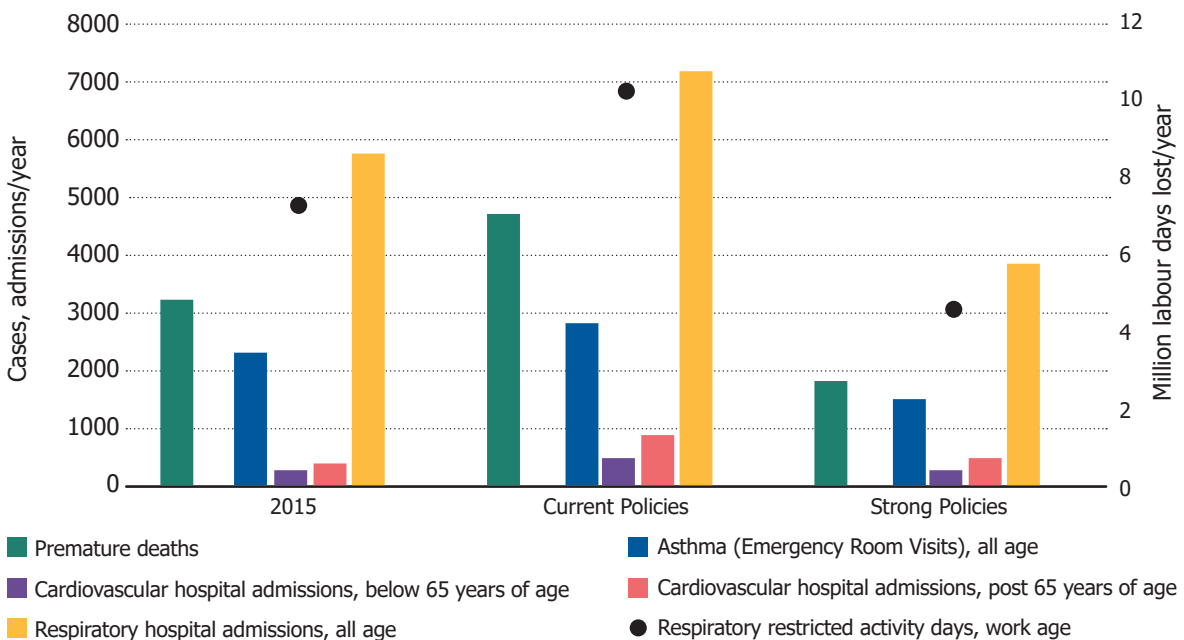


**Fig. 2.6** Monetized morbidity burden from PM<sub>2.5</sub> exposure in 2030, comparing the Current Policies scenario, and effective implementation of all measures (Strong Mitigation scenario)

Fig 2.7 provides a summary of premature death, hospital admissions, and working days lost due to ambient PM<sub>2.5</sub> 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 2,200 asthma related emergency room visits, 200 hospital admissions for cardiovascular reasons, 5,700 respiratory related hospital admissions, and 7.2 million days of restricted activity for respiratory reasons among the working age population are attributed to PM<sub>2.5</sub> 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 almost 4,000 as well as reducing the number of emergency room visits from asthma by 1,500 and avoiding 3,200 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 a switch to clean cooking for which monetized benefits from introducing the measure in Cambodia alone are estimated at about 190 million USD per year from ambient PM<sub>2.5</sub> only. Prevention of forest fires within Cambodia and surrounding countries could bring health benefits of 150 million USD per year, on top of benefits from avoided ecosystem damage. Electrification of road transport and strict emission standards for remaining combustion vehicles in Cambodia could avoid health damages worth 100 million USD per year, with vehicle inspection and maintenance adding another 20 million USD. Solutions which improve municipal waste management could result in benefits of almost 90 million USD per year. Increasing renewables and applying efficient post combustion controls in the power and industrial sectors as well as improving industrial production standards could bring benefits of 65 million USD. Measures in the agriculture sector are estimated to have a smaller potential, except the prevention of agricultural waste burning.

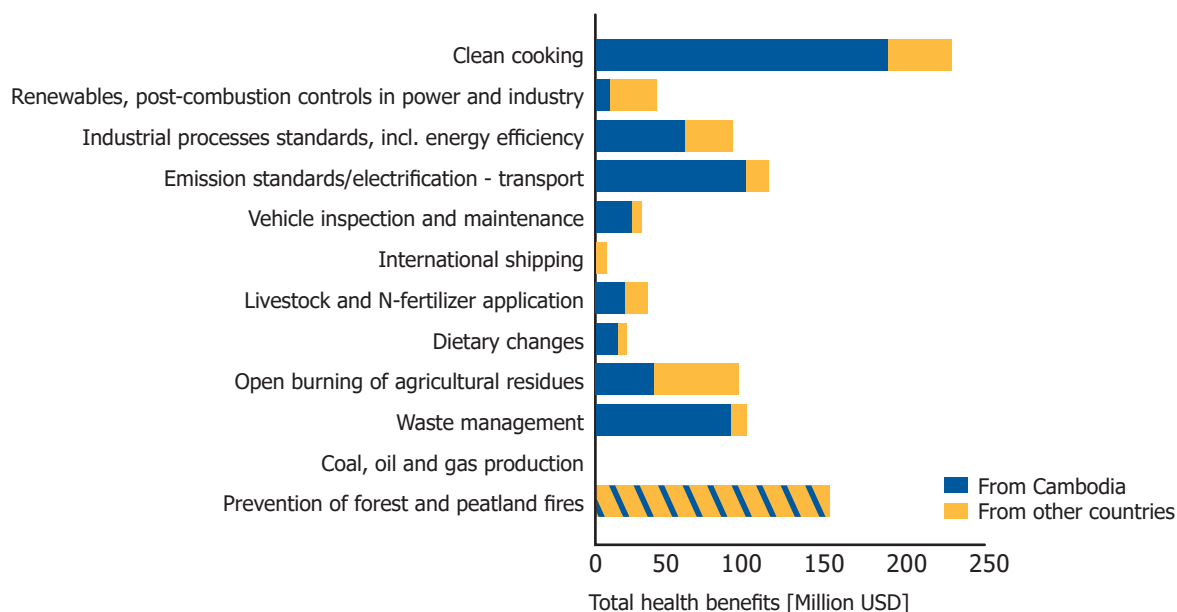


**Fig. 2.7** Summary of the incidence of included impacts estimated for 2015 and analyzed scenarios. Deaths, emergency room visits and hospital admissions are shown on the left axis, restricted activity days (dots) use the right axis



Fig. 2.8 distinguishes the benefits gained from the implementation of measures in Cambodia (blue), and in the other ASEAN countries (yellow). It is therefore clear, especially in some specific areas that a large benefit can be reaped from collaboration on air quality action. While it is also likely that other ASEAN countries would benefit from implementation of ambitious air quality actions in Cambodia. While the

numbers mentioned in the previous paragraph refer to the implementation of measures in Cambodia, the initial assessment shows that implementation of all 12 solutions in the whole ASEAN region would bring another 0.2 billion USD per year of avoided damage costs in Cambodia, in addition to those avoided by action in Cambodia itself.



**Fig. 2.8** Monetized health benefits from individual measures applied in 2030 on top of current policies, distinguishing benefits from measures applied in Cambodia, and in the whole ASEAN region. Note that for forest and peatland fires, the model does not distinguish between the impacts from preventing fires in Cambodia or in other countries

### 2.3. Climate and other co-benefits

This assessment has estimated the costs that Cambodia 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 Cambodia 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<sub>2.5</sub> concentration reductions with emission reductions for CO<sub>2</sub> and methane (CH<sub>4</sub>) (converted to CO<sub>2</sub>-equivalent emissions using Global Warming Protocol (GWP)-100) from implementing each solution.

In 2030, two of the most important measures for air quality also have significant co-benefits for GHG reductions: The largest potential for reducing GHG emissions are for the solutions related to electrification in the road transport sector as well as the transition to

clean cooking, each of which could reduce Cambodia’s GHG emissions by 1 Mt CO<sub>2</sub>-eq annually in 2030 while simultaneously reducing population weighted PM<sub>2.5</sub> exposure by 2 µg/m<sup>3</sup> (cooking) and 1.3 µg/m<sup>3</sup> (transport), respectively. 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.

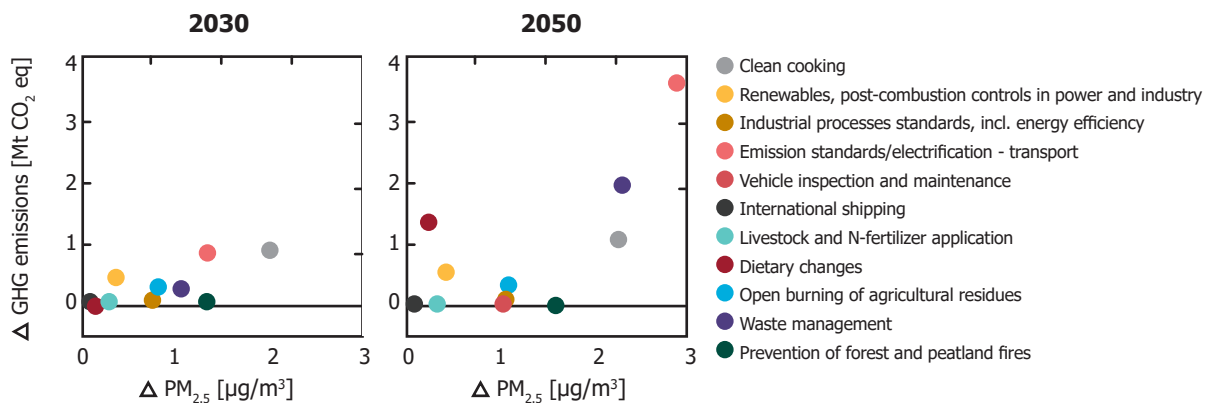
GHG reductions from clean cooking are due to large efficiency gains despite a transition from biofuel to LPG; they could be even larger if the transition is made directly to electric stoves, to the extent possible, provided that the electricity is generated from renewables. The switch to renewables in power and industry itself has significant co-benefits when combined with efficient end-of-pipe air pollution

emission abatement although the contribution from these sectors to pollution in Cambodia is smaller. Also, several other measures have a potential for co-benefits, for example improved municipal waste management or agricultural waste burning, through avoided CH<sub>4</sub> emissions.

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. Also, the co-benefits of better waste management avoiding both open burning of waste and CH<sub>4</sub> emissions from landfills are much more pronounced in 2050; by then, this sector is expected

to double its contribution to ambient PM<sub>2.5</sub> if the measure is not taken. With the expected increase in meat consumption under the Current Policies scenario, a switch to healthier diet has a significant potential for GHG abatement in 2050.

Cambodia has set ambitious targets to reduce GHG emissions in the country by 42% in 2030 compared to a baseline scenario, 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 Cambodia's Nationally Determined Contribution (NDC), the Phnom Penh Sustainable City Plan, or the National Environmental 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<sub>2</sub> + CH<sub>4</sub>) 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 (EANET, 2020; Ministry of Environment, 2021) show that the assumptions about policies considered in the Current Policies scenario are largely complete and consistent with the existing legislative framework in Cambodia 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 (Ministry of Environment, 2021), 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, 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 based on a combination of local and international data (for details, see Annex 1).

### 3.3. Modeled PM<sub>2.5</sub> concentrations

There was only very limited information available to validate the ambient PM<sub>2.5</sub> concentrations calculated in GAINS against observations. Annual mean PM<sub>2.5</sub> concentration levels in downtown Phnom Penh modelled by GAINS in 2015 (26 µg/m<sup>3</sup>) are only slightly higher than those measured by the Ministry of Environment with their monitoring station in 2018-

2021 (19-21 µg/m<sup>3</sup>) but it is impossible to assess the model performance for the whole country from a single monitoring point. Attributable deaths estimated for current levels of PM<sub>2.5</sub> are very close to the values reported by the GBD study (in 2015 the GAINS estimate is slightly higher by 7%).

### 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 0.3-0.4 billion USD, which represents nearly half of the estimated cost of inaction. However, as noted earlier, this estimate does not include costs of transformation towards higher share of renewables, alternative diets, etc. In relative terms, the initial cost estimates represent a larger share of the cost of inaction than

in other ASEAN countries, primarily because the current legislation addressing transport and industry (as reflected in the Current Policies scenario) is less stringent than in some of the other countries in the region.

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  $SO_2$ ,  $NO_x$ ,  $NH_3$  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

Cambodia bears a high health burden from exposure to ambient PM<sub>2.5</sub> 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 the increasing trends in emissions and air pollution impacts. Building upon the assessment for clean air in the ASEAN region and aligning with Cambodia's Clean Air Plan, 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. This study also highlights the importance and benefits of collaboration within the ASEAN region since pollution knows no boundaries and internationally coordinated efforts to reduce emissions will benefit most countries within the region.

Not implementing such actions or lack of further action will have direct economic costs. An initial 'cost of inaction' has been estimated here for Cambodia as reaching around 800 million USD in 2030, considering the economic costs of mortality and morbidity due to air pollution exposure only. While including other impacts or foregone benefits in the assessment will likely increase this cost further. Introducing policies stimulating the rapid introduction of identified further mitigation measures would result 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 nearly half of the cost of inaction.

Key policies delivering major benefits from both assessments include those related to:

- A complete transition to clean cooking fuels,
- Prevention of forest and peatland fires within Cambodia and in the surrounding region,

- Improved waste management, including reducing the amount of waste which is openly burned,
- 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, most prominently from effectively banning open burning of agricultural residues,
- Finally, internationally coordinated efforts to reduce emissions, including exchange of experience in successful development and application of policies and their enforcement will have benefits going beyond the national borders.

Implementing all of the clean air actions will also have important co-benefits including for climate change and sustainable development. This assessment found that several of the measures to reduce air pollution would simultaneously reduce emissions of GHGs, with larger reductions in the long-term translating by 2050 into significant reductions of CO<sub>2</sub> and CH<sub>4</sub>. Among the most important measures delivering these longer-term benefits for simultaneously reducing air pollution and emissions of GHGs in the long term include the electrification of the vehicle fleet for transport, more effective waste management policies and the transition to clean cooking technologies.



# 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<sub>2.5</sub>. The necessary ingredients for this calculation are the ambient PM<sub>2.5</sub> 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 <https://gains.iiasa.ac.at>) is the central tool used in the analysis. GAINS, developed by the International Institute for Applied Systems Analysis (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<sub>2.5</sub> and its precursor pollutants, to calculate ambient PM<sub>2.5</sub> concentrations arising from the emissions, as described further in Section 1.2, and to evaluate the health impacts as detailed below.

From ambient PM<sub>2.5</sub> concentrations, health impacts in terms of mortality and morbidity are calculated. All outcomes are listed in Box 1. GAINS routinely

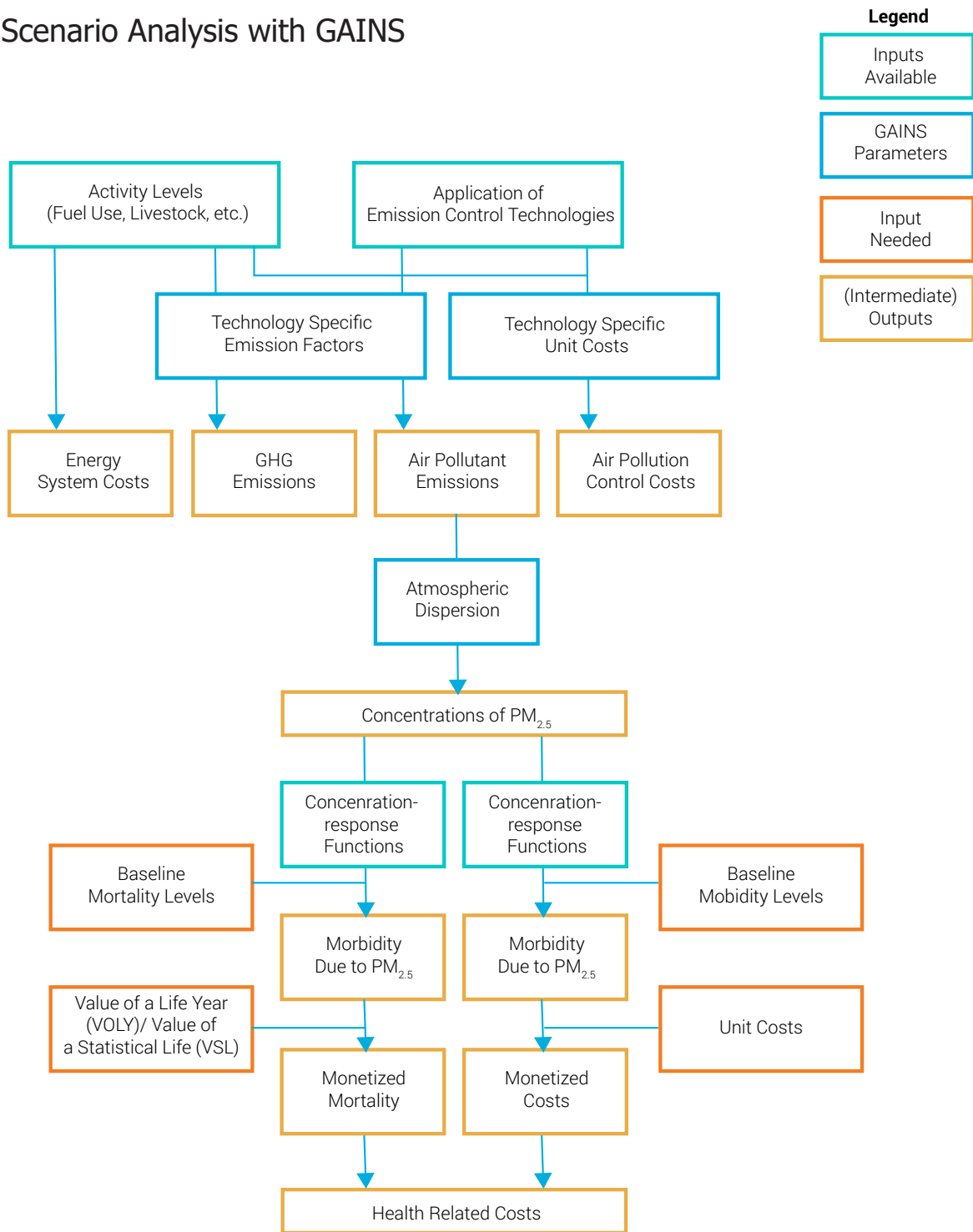
quantifies health impacts in terms of premature deaths and YLLs from six diseases in line with the methodology developed within the GBD assessments (Murray et al., 2020). Within this assessment, impact calculations have been extended to cover morbidity related to cardiovascular and pulmonary diseases. 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 concentration-response functions 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<sub>2.5</sub>,

$$PAF_{da} = \frac{\sum_n pop_n \cdot (RR_{nda} - 1)}{\sum_n pop_n \cdot RR_{nda}} \quad 1$$

where  $RR_{nda}$  is the relative risk for annual mean PM<sub>2.5</sub> 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.

## Scenario Analysis with GAINS



**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

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

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 Global Burden of Disease 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:

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

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:

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

where:

- $i, k, m, p$  Source region, activity type, abatement measure, pollutant, respectively
- $E_{i,p}$  Emissions of pollutant  $p$  (for  $\text{SO}_2$ ,  $\text{NO}_x$ , NMVOC,  $\text{NH}_3$ ,  $\text{PM}_{2.5}$ ) in source region  $i$ . Emissions of GHGs ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ) 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.

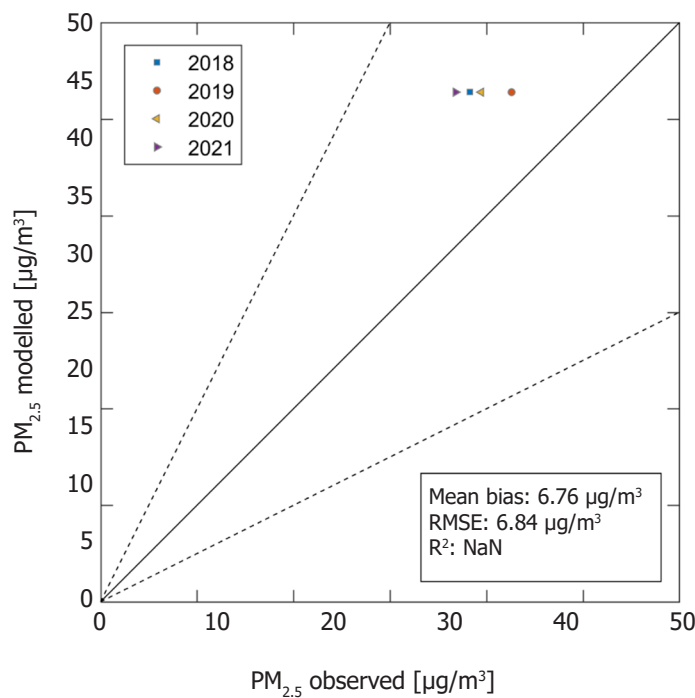
Transport Model (Simpson et al., 2012) as described in the Supplementary Information to (Amann et al., 2020).  $\text{PM}_{2.5}$  concentrations are calculated on a  $0.1^\circ$  grid (roughly  $10 \times 10 \text{ km}$ ) and thus correspond to urban background levels, not to pollution hotspots.

To calculate ambient  $\text{PM}_{2.5}$  concentrations, GAINS uses a linear approximation of the EMEP Chemistry

### Validation of ambient $\text{PM}_{2.5}$ concentrations

Fig. 2 shows a comparison of modelled  $\text{PM}_{2.5}$  concentrations for 2015 against monitoring data for recent year provided by the Ministry of Environment. Only one station was available, located in Phnom Penh.

Concentrations measured there are reproduced well in GAINS even if there seems to be some overestimate. However, assessing the quality of the modelling for the whole country from one single station is not possible.



**Fig 2.** Comparison of  $\text{PM}_{2.5}$  concentrations modelled with GAINS for 2015 against observations from 2018 to 2021

## Concentration-response functions (CRFs)

Concentration-response functions 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  $\beta$  derived from the regression analysis as

Asthma-related emergency room visits	0.0034/ $\mu\text{g}/\text{m}^3$
Cardiovascular hospital admissions (pre 65 years)	0.0009/ $\mu\text{g}/\text{m}^3$
Cardiovascular hospital admissions (post 65 years)	0.0013/ $\mu\text{g}/\text{m}^3$
Respiratory hospital admissions	0.0013/ $\mu\text{g}/\text{m}^3$
Respiratory restricted activity days (working age)	0.0102/ $\mu\text{g}/\text{m}^3$

Although the CRFs are for outcomes which typically relate to impacts of short-term exposure to  $\text{PM}_{2.5}$ , they are applied here to the annual mean concentrations. Ru et al. (in review) 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 for cardiovascular reasons 2018-2021 have been made available to this assessment by the Ministry of Health. We used only

2019 data in order to avoid possible temporary effects during the Covid-19 pandemic.

## 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 GBDs 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

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:

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

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.e., 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.

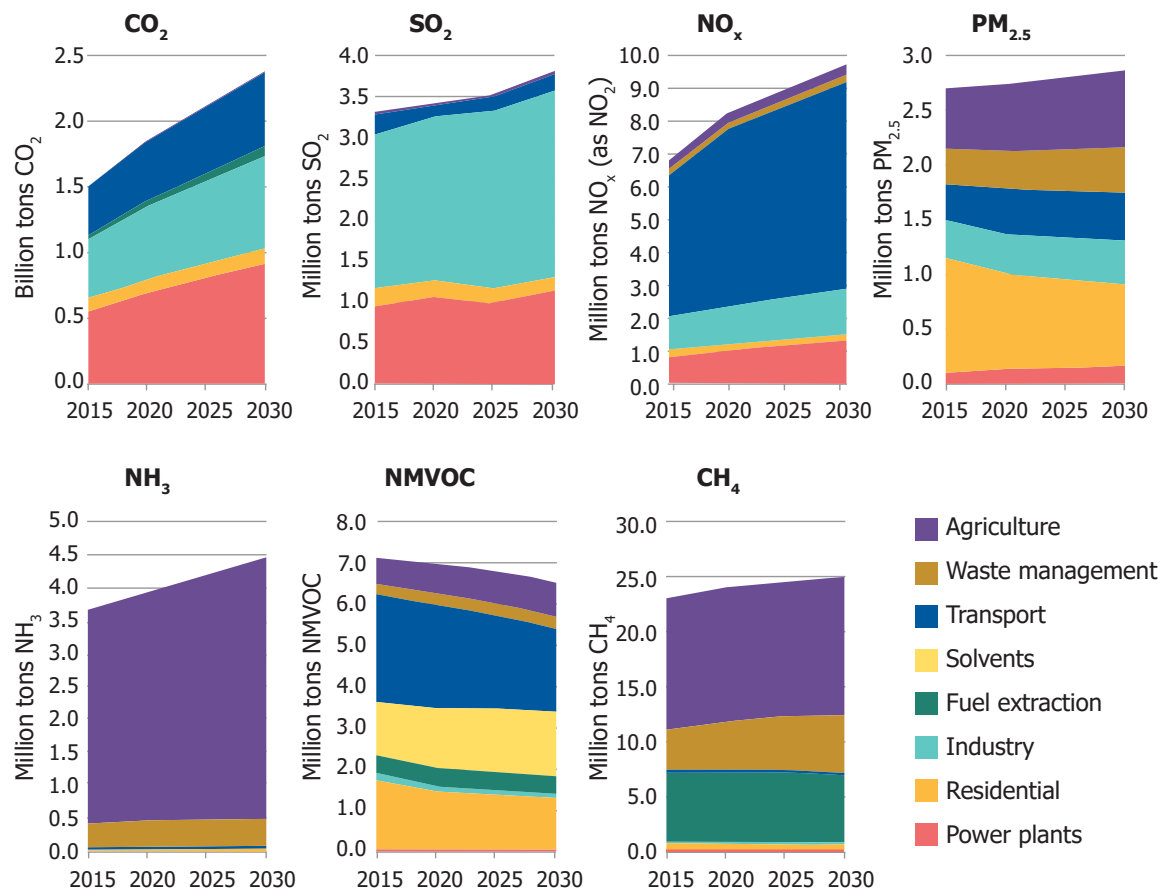
### Current Policies

As a result of the continued strong economic growth, the modelling anticipates significant increase of CO<sub>2</sub> 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<sub>2</sub> 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 (NPS) 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<sub>2</sub>, 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<sub>2</sub> (Fig. 3).

Another notable trend involves residential cooking, a sector that contributes a significant share of primary PM<sub>2.5</sub>. For primary PM<sub>2.5</sub> 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<sub>2</sub>, primary PM<sub>2.5</sub>, key precursors of ambient PM<sub>2.5</sub> and CH<sub>4</sub> for the ASEAN region in the Current Policies scenario

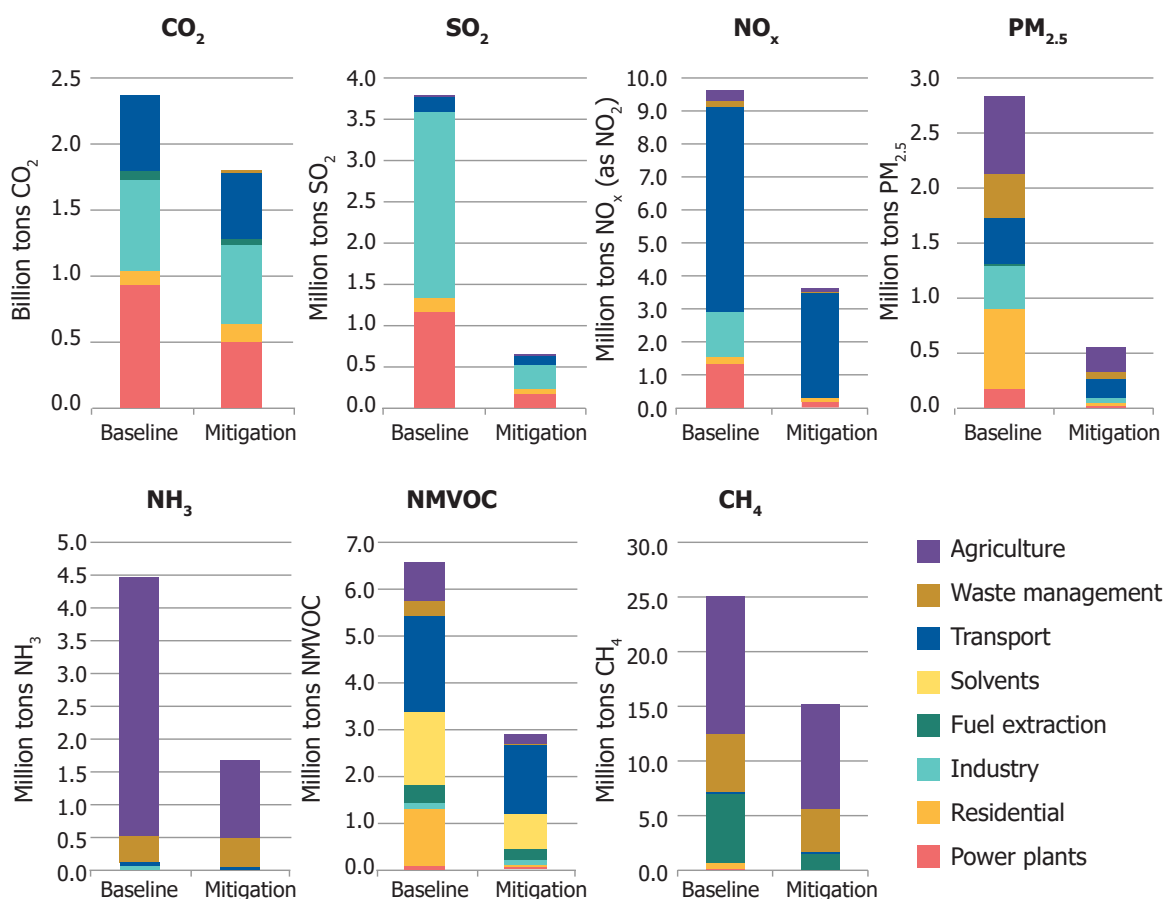
## Strong Mitigation

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 caloric 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<sub>2</sub> 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<sub>2</sub>, primary PM<sub>2.5</sub>, key precursors of ambient PM<sub>2.5</sub> and CH<sub>4</sub> for the ASEAN region in the Current Policies (Baseline) and Strong Mitigation scenario estimated for 2030

While CO<sub>2</sub> 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% (SO<sub>2</sub>), and emissions of CH<sub>4</sub> 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)<sup>4</sup> and also UNEP (2019) reports.

## 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<sub>2.5</sub>.

As shown in the national assessment report, several of these measures also bring strong co-benefits including reduction of GHG 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 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 desulphurization, 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 sulphur fuel, i.e., 0.5%S in heavy fuel oil with further reduction to 0.1%S, introduction of particulate filters and NO <sub>x</sub> Reduction Selective Catalyst Reduction (deNO <sub>x</sub> SCR) installations. Alternatively, flue gas desulfurization can be installed to achieve the same reduction of sulfur dioxide (SO <sub>2</sub> ) as when using low sulfur fuel.
Livestock and N fertilizer application	Control of ammonia 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.

<sup>4</sup> That report identified 15 solutions which included measures targeting reduction of CH<sub>4</sub> and Hydrofluorocarbons (HFCs), i.e., rice paddies, wastewater treatment, and HFC-refrigerant replacement.

12 solutions	Brief description
Prevention of forest, peatland fires	Improved forest, land and water management and fire prevention strategies. Enhance collaboration through ASEAN Agreement on Transboundary 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 methane, 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 sustainable development scenarios.

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