NATIONAL ASSESSMENT OF THE COST OF INACTION OF TACKLING AIR POLLUTION IN THAILAND

International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

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ACRONYMS

ASEAN	Association of Southeast Asian Nations
BC	Black Carbon
CH_4	Methane
CO_2	Carbon Dioxide
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
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
LPG	Liquefied Petroleum Gas
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
PM	Particulate Matter
SDGs	Sustainable Development Goals
SDS	Sustainable Development Scenario
SLCPs	Short Lived Climate Pollutants
SO_2	Sulphur Dioxide
UN	United Nations
UNEP	United Nations Environment Programme
UNEP – CCAC	United Nations Environment Programme – Climate and Clean Air Coalition
VOLY	Value of a Statistical 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 Thailand. It quantifies and compares the potential health costs in two alternative future 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 be missed if further measures are not implemented. The key findings of this initial assessment are:

Thailand 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 Thailand. 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 24 thousand premature deaths due to ambient air pollution exposure in Thailand per year by 2030.

Further action could have significant health benefits for the population of Thailand. Implementing further policies beyond current legislation could avoid 17 thousand premature deaths, 16 thousand hospital admissions and almost 12 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 2.0% of Thailand's Gross Domestic Product (GDP) in 2030. Lack of immediate further action on air pollution could cost Thailand 12.5 billion USD a year in 2030, based on a selection of mortality and morbidity impacts of air pollution. This equals about 2.0% of Thailand'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 Thailand include a complete switch to clean cooking technologies, increased renewable electricity generation capacity, policies supporting accelerated introduction of electric vehicles and strengthened emission standards for road transport, effective waste management strategies, and bans on agricultural residue burning. 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 reduce GHG emissions with benefits for climate change and could help Thailand 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 Thai 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. Thailand is not exempt from this burden; exposure to fine particulate matter ($PM_{2.5}$) was estimated to cause about 32,000 premature deaths annually in Thailand 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, 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 Thailand, 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 ((Nikam, Archer and Nopsert, 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 (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), as well as having other benefits such as achieving the SDGs. The United Nations Environment Programme – Climate and Clean Air Coalition (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, The United Nations Environment Programme (UNEP), Association for Southeast Asian Nations (ASEAN), and Climate and Clean Air Coalition (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 short-lived climate pollutants (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 Thailand 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 Thailand, 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 Thailand 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 total 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: a 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.

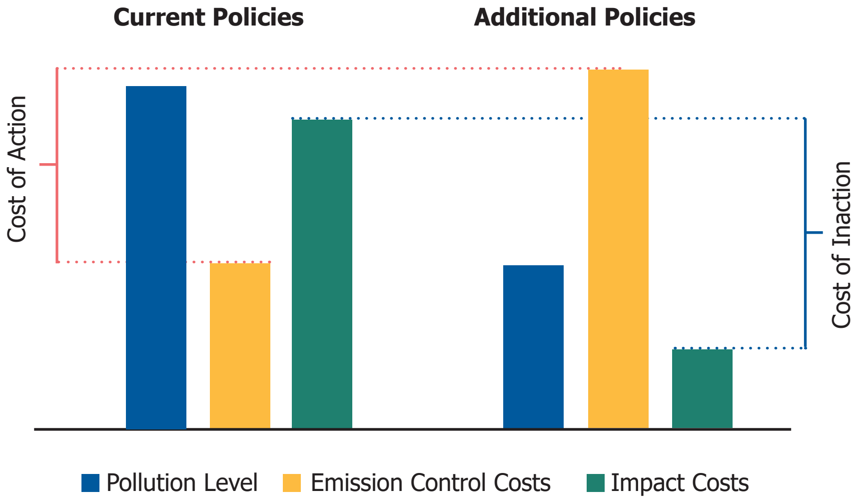

Fig. 1.1 *Schematic picture of the proposed approach for quantifying the cost of action vs cost of inaction, relying on the comparison of Current Policies and Additional Policies*

The Current Policies case is associated with a certain level of ambient air pollution (symbolized by the blue bar in Fig. 1.1), costs for implementation of existing pollution legislation (the yellow bar), and a certain level of related costs (the green 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 cost of action is then defined as the difference between the emission control costs in the Current Policies and Additional Policies scenarios, whereas the cost of inaction is 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 GHG – Air pollution Interactions and Synergies (GAINS)[1] model (Amann et al., 2011; UNEP, 2019) developed at the International Institute for Applied Systems Analysis (IIASA) (see Box 2 below 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 related to morbidity (cardiovascular and respiratory hospital admissions, asthma related emergency room visits, and restricted activity days) 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 years of life lost (YLLs) (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[1].

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 measurements; more than 1000 technologies to control emissions are represented. The mitigation options include impact on emissions of all key air pollutants (SO_2, NO_x, PM (including black carbon (BC) and organic carbon (OC)), NMVOC, 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 concentration-response functions from the international literature, GAINS calculates premature mortality from long-term exposure to $PM_{2.5}$, and the associated 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.

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[1] For more details about the GAINS model, please visit: https://gains.iiasa.ac.at/models.

1.5. Scenarios

To calculate the cost of inaction from air pollution, as illustrated in above 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, following analysis by Nikam, Archer and Nopsert (2021). 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 Report (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 Thailand will experience significant economic development in the future with its GDP growing by nearly 70% to 2030 from 401 billion USD in 2015, following the projections made in the International Energy Agency's World Energy Outlook 2018 (International Energy Agency [IEA], 2018). Following the United Nations (UN) World Population Prospects 2017 (United Nations [UN], 2017), Medium Scenario, the population of Thailand is also assumed to change, growing from 68.6 million in 2015, to a maximum of 69.7 million in 2025, before decreasing slowly to 65.4 million in 2050, while the average age of the population is also projected to increase.

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 Thailand by mid-2020. The information about current policies, emission limit values and standards is taken from Motokura et al. (2017), Dieselnet (n.d.), He et al. (2021) , and a recent review of air quality relevant policy landscape in Thailand (Nikam, Archer and Nopsert, 2021). The energy trends used in the Current Policies scenario are consistent with the IEA 'New Policy 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 Report (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[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 GHG emissions and contribute to the achievement of several SDGs.

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[2] 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 $PM_{2.5}$ 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

2.1. Emissions and ambient concentrations

This section presents results from the assessment itself. Section 2.1 quantifies the emissions and ambient PM2.5 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.

2.1.1 Current policies scenario

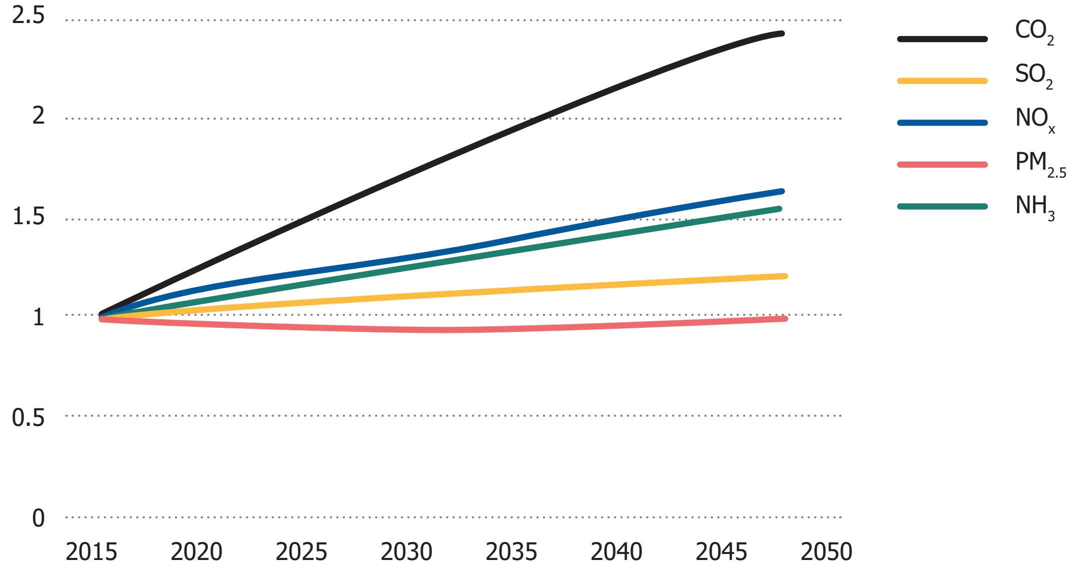

Fig. 2.1 *Trends in emissions of* CO_2 *and air pollutants in the Current Policies scenario for Thailand*

In the Current Policies scenario, the assumed implementation of existing and recently introduced legislation already shows some effect at slowing the growth of emissions of $PM_{2.5}$ and key PM precursor pollutants (sulphur dioxide (SO_2), nitrogen oxides (NO_x), Ammonia (NH_3), non-methane volatile organic compounds (NMVOCs) (Fig. 2.1). However, current policies are not sufficient to offset the increase in fuel use and production activities, which combined with assumed strong economic growth in Thailand drives the significant increases in carbon dioxide (CO_2) emissions (Fig. 2.1). The fact that the emissions of air pollutants are growing slower than those of CO_2, suggesting gradual decoupling of economic growth from air pollutant emissions. Thailand has been promoting clean cooking and has achieved significant reduction of emissions of PM precursors through providing access to clean fuels both in urban and rural areas. However, significant further reductions were not identified in existing policies and legislation and therefore by 2030 in the Current Policies scenario about a quarter of primary $PM_{2.5}$ emissions still originate from this source.

Annual mean $PM_{2.5}$ concentrations in Thailand estimated by GAINS are between 5 and 40 $\mu g/m^3$ in 2015 (Fig. 2.2, left panel), with only a very small share of the population exposed to the highest concentration levels. While this means that the $PM_{2.5}$ pollution problem in Thailand is smaller than in many other Asian countries, concentrations are still considerably above the World Health Organization (WHO) guideline values of 5 $\mu g/m^3$ (World Health Organization [WHO], 2021), particularly in cities. It should also be noted that the modelled concentrations quantified here are less than the measured concentrations at Thai monitoring sites (which may be influenced by local sources below the model resolution). This means that the conclusions drawn here are likely to be a lower estimate, and the actual exposure levels in certain areas could be higher than those quantified here. A validation of concentration levels estimated by GAINS against monitoring data is shown in the Annex.

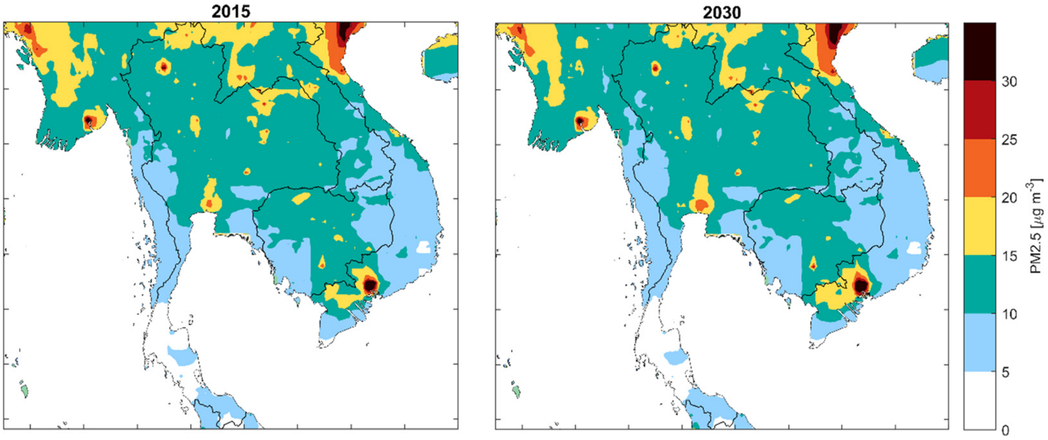

Fig. 2.2 *$PM_{2.5}$ concentrations for Thailand modelled with the GAINS model for 2015 (left) and for 2030 under Current Policies (right)*

Even assuming the successful implementation of existing policies and legislation, there is little improvement in $PM_{2.5}$ concentrations by 2030 in the Current Policies scenario (Fig. 2.2 right panel). This is also illustrated in Fig. 2.3, which shows the distribution of population exposure to $PM_{2.5}$. In 2015, 94% of the population were exposed to $PM_{2.5}$ levels above the current WHO air quality guideline of 5 µg/m^3 and over 80% were exposed to levels above the 2005 WHO guideline of 10 µg/m^3 (redefined as Interim Target 4 in the 2021 WHO Guidelines), while 28% were exposed to levels between interim targets 2 and 3 (15-25 µg/m^3), and 1% at concentrations higher than 25 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 80% of the population could still be experiencing concentrations above the 2005 WHO guideline of 10 µg/m^3 (now Interim Target 4) and the number of people exposed to concentrations exceeding 15 µg/m^3 would also grow from 19 to more than 23 million due to increasing concentrations in some regions (Fig. 2.2) and continued 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. 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 8 million people would enjoy PM concentrations below the current WHO guidelines and only 2% would be exposed to levels above 10 µg/m3 compared to more than 80% in the Current Policies scenario. 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.

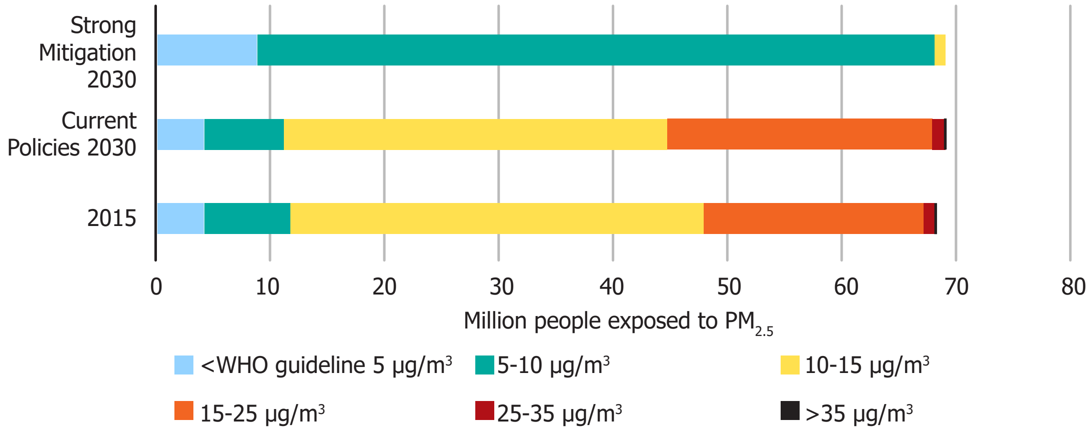

Fig. 2.3 *Population exposure to PM$_{2.5}$ modelled with the GAINS model for 2015 and for 2030 under different scenarios*

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 Thailand in 2030, assuming the full implementation of each solution both in Thailand but also across the whole ASEAN region. This figure also shows the impact on exposure from measures which had already been implemented by 2015 (dark 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 (light 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 and SO$_2$ emissions from electricity generation and industry have already contributed to large improvements in air quality in Thailand, estimated to have already resulted in 5 μg/m^3 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 around 2 μg/m^3 (dark blue and light 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 clean cooking (eliminating solid fuels in the residential sector), waste management (elimination of open waste burning), and further measures controlling large point sources such as power and industry, as well as further measures in the transport sector. The latter also include the electrification of road transport, while the measures in power and industry sectors include a transition to renewable energy and efficiency improvement.

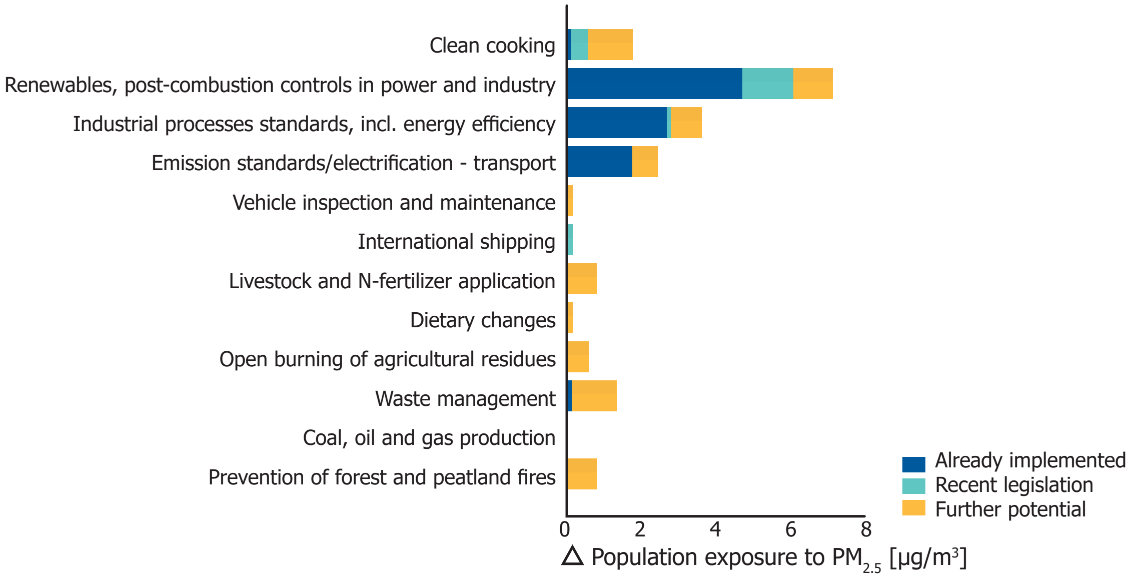

Fig. 2.4 *Expected improvement in population-weighted mean PM$_{2.5}$ concentrations in Thailand from each of the 12 solutions in 2030, distinguishing already implemented measures (dark blue), legislation passed after 2015 but not yet fully implemented (light green), and the further potential (yellow)*

2.2. Health impacts and cost of inaction

Exposure to $PM_{2.5}$ leads to considerable health impacts in Thailand. The GAINS model estimates that in 2015, more than 16,000 premature deaths were attributable to ambient $PM_{2.5}$, corresponding to 313,000 YLLs. These estimates are lower than the numbers published by the GBD and likely constitute a lower range. As mentioned in Section 2.1, $PM_{2.5}$ concentrations estimated by the GAINS model are low biased against monitoring stations, which may at least partly explain this difference. 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 almost 24,000 premature deaths and 413,000 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 2.1 below, 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 years of life lost (YLL) in combination with the value of a statistical life year (VOLY). As is usually the case, we find that the approach monetizing 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 YLLs monetization approach for valuating loss of human life.

Unit costs, VSL and VOLY shown in below Table 2.1 combine local information with internationally available data sets adapted to Thailand's per-capita GDP.

Table 2.1 *Morbidity and mortality attributable to ambient PM2.5 in Thailand in 2015 and 2030 under current legislation as well as Strong Mitigation implemented across all ASEAN, and their associated impact costs. For mortality, premature deaths and YLLs are alternative indicators and are shown for comparison only*

Indicator	Health Impacts in Physical Units [cases/year]			Unit cost [USD 2015]	Impact Costs [Thousand USD 2015/year]		
	Historical	Current Policies	Strong Mitigation		Historical	Current Policies	Strong Mitigation
	2015	2030	2030		2015	2030	2030
Mortality							
Premature deaths	16,453	23,998	6,530	1,094,019	17,999,895	26,254,268	7,143,944
YLLs	315,588	413,094	114,036	41,370	13,055,996	17,089,853	4,717,719
Morbidity							
Asthma (Emergency Room Visits), all age	20,332	21,603	9,867	15	310	330	151
Cardiovascular hospital admissions, below 65 years of age	2,815	2,705	1,154	920	2,589	2,487	1,061
Cardiovascular hospital admissions, post 65 years of age	5,167	10,074	4,645	920	4,751	9,263	4,271
Respiratory hospital admissions, all age	16,236	17,257	7,956	920	14,930	15,869	7,316
Respiratory restricted activity days, working age	31,838,063	36,508,057	13,469,368	33	1,064,200	1,220,297	450,219

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 Thailand are estimated to reach approximately 18 billion USD per year, a value equal to 2.7% of Thailand's GDP[4] due to little improvement in air quality. 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 5.8 billion USD per year, equivalent to about 0.8% 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 Thailand is estimated to be 12.5 billion USD per year, equivalent to around 2.0% 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.

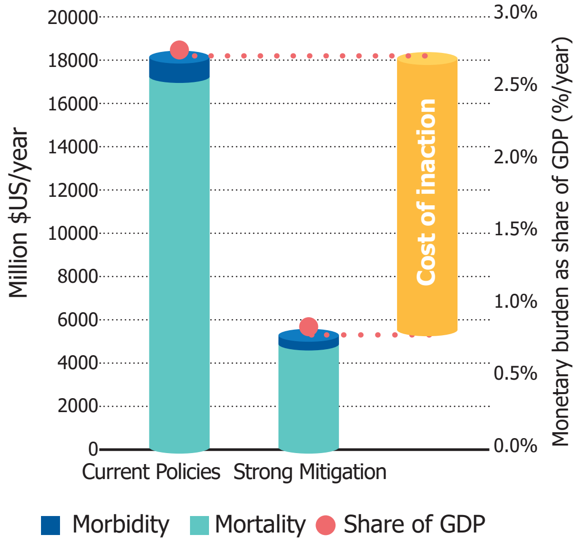

Fig. 2.5 *Monetized health burden from $PM_{2.5}$ exposure in 2030, comparing the Current Policies scenario, and effective implementation of all measures assessed in this study for Thailand (Strong Mitigation case). Stacked Bars – Left axis: Burden expressed as million USD per year, Pink dots – Right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

Most of the economic burden from the costs of inaction – or the costs of not implementing all measures-is associated with mortality (shown here is the monetized estimate for YLLs) representing consistently about 90% of costs. The remaining 10% are dominated (98%) by costs associated with respiratory restricted activity days, which are monetized here as working day losses (Fig. 2.6).

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[4] GDP values are projected for the respective year, expressed in terms of 2015 USD like all other costs. The comparison to GDP is given as a reference only; damage costs do not directly represent economic losses since they contain a large share of non-market costs from monetized loss of life expectancy.

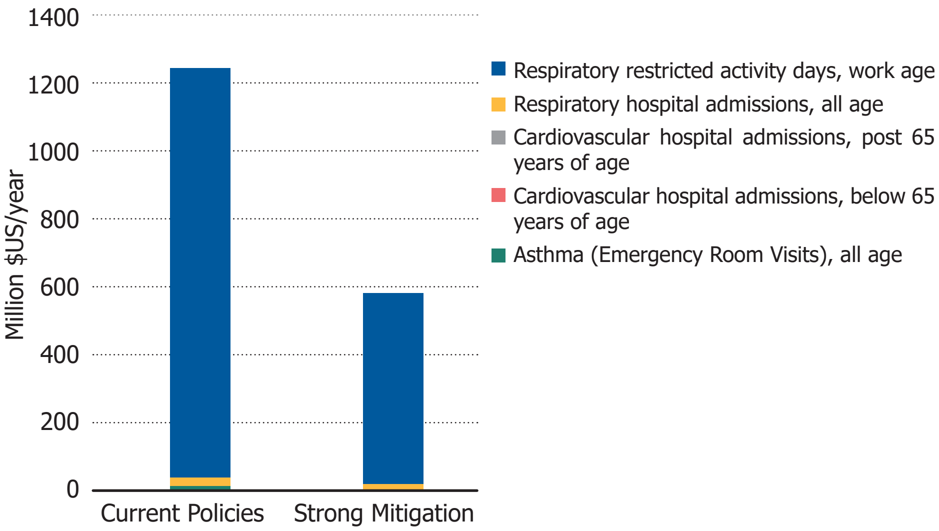

Fig. 2.6 *Monetized morbidity burden from* $PM_{2.5}$ *exposure in 2030, comparing the Current Policies scenario, and effective implementation of all measures (Strong Mitigation scenario)*

Fig. 2.7 provides a summary of premature death, hospital admissions, and restricted activity days due to ambient PM2.5 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 20,000 asthma related emergency room visits, 4,000 hospital admissions for cardiovascular reasons, 16,000 respiratory related hospital admissions, and almost 32 million days of restricted activity for respiratory reasons among the working age population are attributed to PM2.5 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 16 thousand as well as reducing the number of emergency room visits from asthma by 12 thousand and avoiding 17 thousand premature deaths (Fig. 2.7).

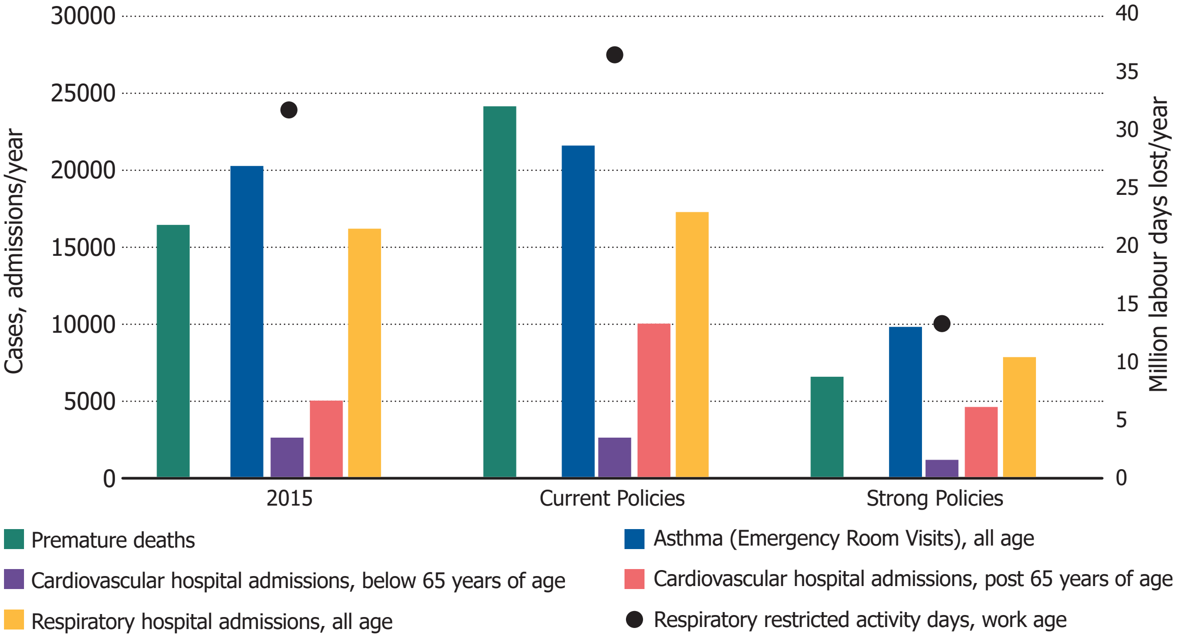

Fig. 2.7 *Summary of the incidence of included impacts estimated for 2015 and analyzed scenarios. Deaths, emergency room visits and hospital admissions are shown on the left axis, restricted activity days (dots) use the right axis*

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 health related 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 the switch to clean cooking for which monetized benefits are estimated at about 2.5 billion USD[5], while increasing renewables and applying post combustion controls in the power and industrial sectors as well as improving industrial standards could bring benefits of nearly 4 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 avoid health damages worth about 3 billion USD. Finally, solutions which address emissions from transport, improve waste management, and improve forest management could result in monetary benefits in the order of 1.5 billion USD per sector.

Thailand is also impacted by transboundary air pollution from neighbouring countries which also contributes to health impacts in Thailand; consequently, Thailand would also benefit from mitigation efforts in those countries. The initial assessment shows that implementation of all 12 solutions in the whole ASEAN region would bring another 0.6 billion USD per year of avoided damage costs in Thailand, in addition to those avoided by action in Thailand itself. Fig. 2.8 directly shows the additional benefits gained from implementation of each of the solutions in Thailand (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 Thailand.

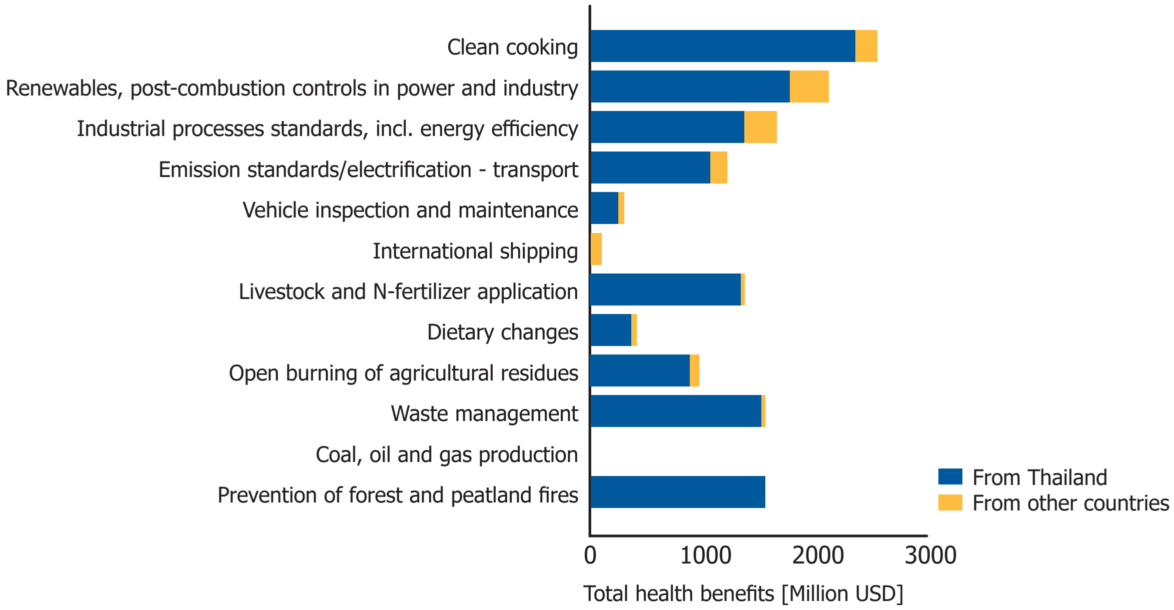

Fig. 2.8 *Monetized health benefits from individual measures applied in 2030 on top of current policies*

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[5] 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.

2.3. Climate and other co-benefits

This assessment has estimated the costs that Thailand 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 Thailand 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 and industry sectors: introducing renewables in the power sector, combined with strict post-combustion emission controls, saves 60 Mt of CO_2 equivalent emissions annually, while also decreasing population average exposure to $PM_{2.5}$ by more than 1 $\mu g/m^3$. Strengthening industrial process standards, in conjunction with the energy efficiency improvements associated with them, also have sizeable benefits for reducing GHG emissions, while the effects of electrification of the car fleet are only marginal in 2030 due to slow vehicle turnover rates. Although not considered in this analysis, it is 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 for reducing congestion and time spent in traffic jams, reduced number of road accidents, as well as additional health co-benefits from active travel.

The measure with the highest potential for $PM_{2.5}$ reduction in 2030, clean cooking, comes with a small negative impact on CO_2 emissions because of the switch from biofuel (which is CO_2 neutral in our accounting under the assumption that the biofuel is sustainably produced) to LPG (liquefied petroleum gas). Given the high benefits of clean cooking for other sustainability goals this should not be an argument against this transition. For example, it would also reduce the health burden from indoor air pollution and help achieving several SDGs, such as improved gender equality (SDG 5) since women are more exposed to indoor air pollution and spend more time cooking with inefficient stoves or collecting firewood. Furthermore, CO_2 emission increases during transition to clean cooking can be avoided by switching directly to electric cooking, instead of LPG, provided renewable energy is used to produce electricity.

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.

Climate policies on their own bring also co-benefits for air pollution, although they might not explore full potential existing via combined air quality and development policies.

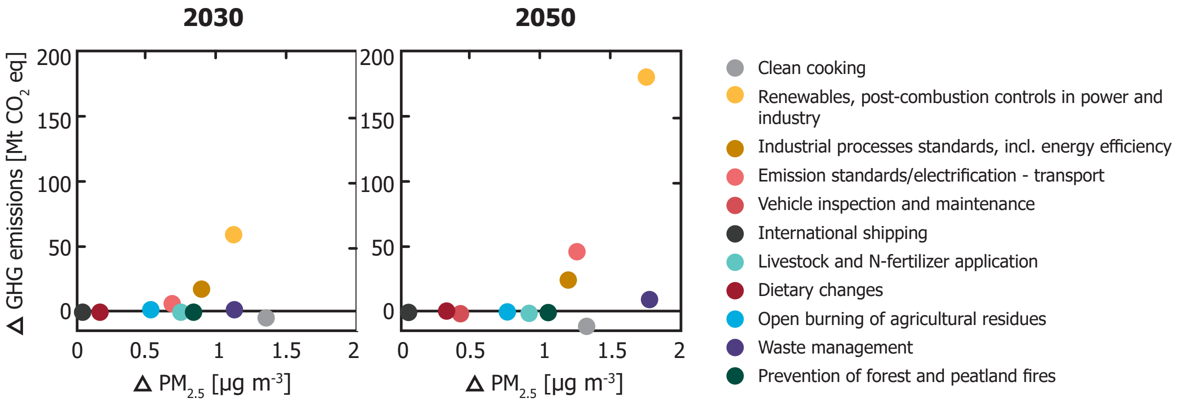

Fig. 2.9 *Co-benefits of individual measures for GHG emissions (CO_2 + CH_4) when fully implemented in 2030 (left) and 2050 (right)*

3. Limitations

3.1. Scenarios and solutions

The analysis presented in this report relies on existing scenarios developed for the Clean Air and Climate Solutions for ASEAN Report (UNEP/CCAC, 2023); 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. Indeed, a review of the recent policy mapping providing a regulatory context and outlook for Thailand (Nikam, Archer and Nopsert, 2021) shows that the assumptions about policies considered in the *Current Policies* scenario are largely complete and consistent with the existing legislative framework in Thailand 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, their reduction potential is captured in the further mitigation potential estimated in the assessment. The same applies for the planned policies which are well represented in the Strong Mitigation scenario.

It was not possible to compare results of this assessment with few existing studies for Thailand where health impacts and benefits were estimated (Chavanaves et al., 2021; Chulabhorn Research Institute, 2018) as they were either performed only for specific regions (cities, provinces) of Thailand, methodologies were different or fully transparent enabling fair comparison.

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. In particular, for hospitalization costs and working day costs, no local data were available.

3.3. Modeled $PM_{2.5}$ concentrations

Although GAINS reproduces the variability of measured ambient $PM_{2.5}$ concentrations throughout the country well, absolute concentrations are underestimated. This likely leads to an underestimate in health impacts and damage costs. The difference to the GBD estimate of $PM_{2.5}$ attributable deaths is almost a factor of 2.

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 4-5 billion USD, which represents about a third 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 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 ozone (O_3) is associated with health and ecosystems impacts and crop loss due to elevated ozone 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 particulate matter 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 cost 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

Thailand 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 12.5 billion USD in 2030 with most costs associated with premature mortality. 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 less than a third of the cost of inaction.

The assessment supports implementation and enforcement of already existing policies in Thailand and shows that the potential scope for mitigation developed in this study is consistent with the most recent plans, although goes beyond and is more ambitious both in terms of pace and efficiency of implementation. This work also aligns with other assessments which are being developed by the Pollution Control Department in Thailand to simultaneously tackle the issues of climate change, air quality and sustainable development. For example, an Integrated Assessment of Air Pollution and Climate Change for Thailand has recently been developed under the Supporting National Action Planning (SNAP) initiative by the Climate and Clean Air Coalition (CCAC). This assessment also directly quantifies the potential for various policies to reduce emissions of air pollutants, short lived climate pollutants and greenhouse gases at the national and regional level in Thailand. Aligning with the assessment presented here, the SNAP assessment identifies key policies which could largely reduce air pollution with benefits for human health as well as reducing emissions of GHGs and SLCPs with benefits for mitigating climate change (CCAC, 2023).

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

- Clean Cooking: A complete transition to clean cooking fuels, ideally directly to electricity,
- 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,
- Road Transport: Electrification of the vehicle fleet, stringent emission controls on the remaining combustion engines,
- Waste Management: More efficient waste management and prevention of open burning of waste,
- Agricultural Burning: Strict enforcement of the ban on agriculture stubble burning; increased prevention of forest fires and wildfires.

Further actions driven by health concerns will also bring 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, concentration-response functions (CRFs) for the selected disease endpoints, and baseline rates for these disease endpoints. Further, particular unit costs are needed for the assessment of impact costs.

A chart of the information flows and calculation steps is shown in Fig 1. The GAINS[1] (Greenhouse gas-Air Pollution Interactions and Synergies) model (Amann et al., 2011) 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. 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 Global Burden of Disease (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 $PM_{2.5}$,

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

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.

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[1] For more details, refer to: http://gains.iiasa.ac.at.

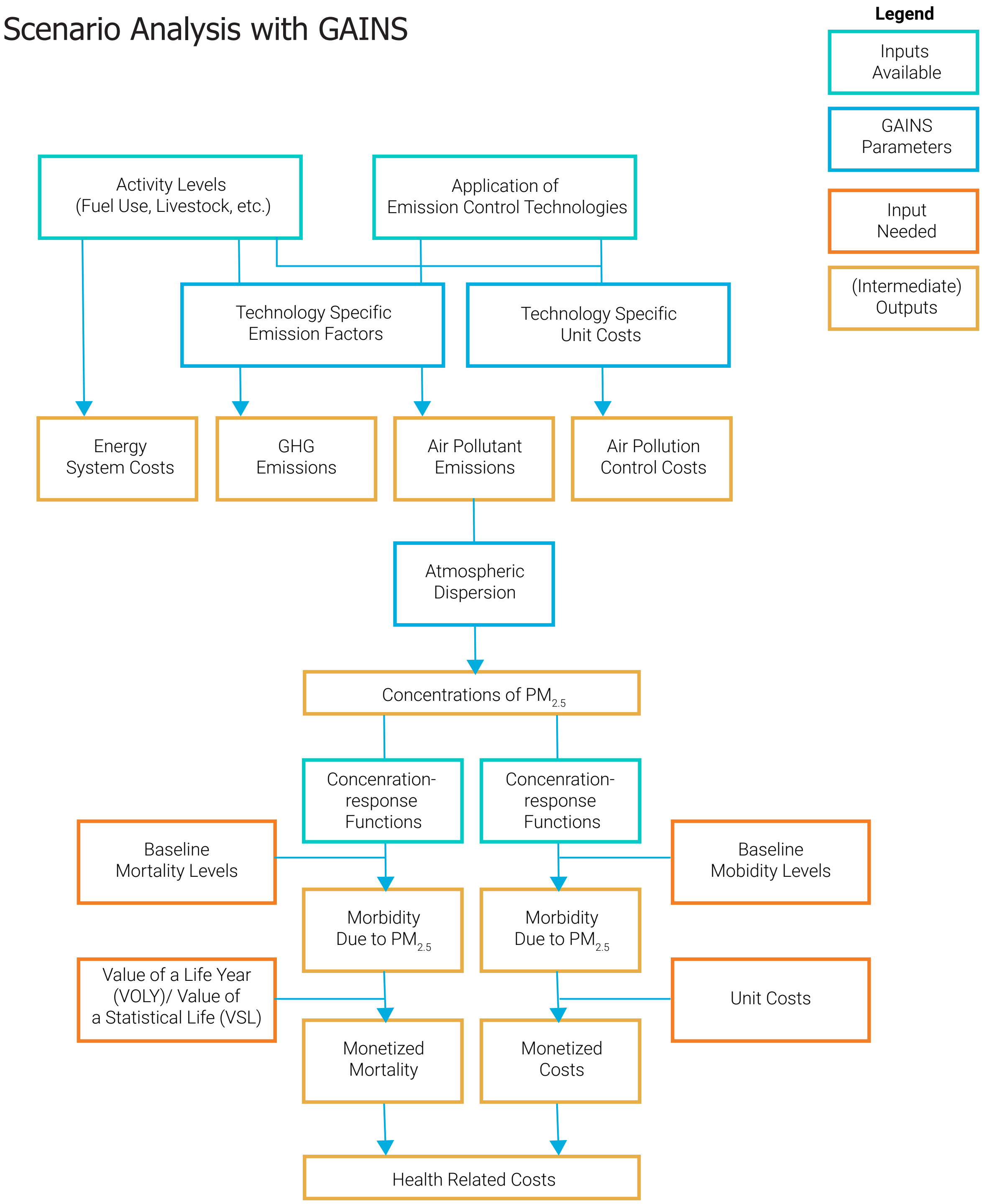

Fig 1. *Flow of information in the GAINS model to assess policy costs and impact related costs for one scenario (Current Policies or Mitigation cases). Orange fields highlight data inputs needed from local partners*

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 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, years of life lost (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 Global Burden of Disease 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 value of a statistical life (VSL) or the value of a life year (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 life years lost (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 PM2.5 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 PM2.5 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, and NMVOC) and greenhouse gases. 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*
$x_{\mathrm{i,k,m,p}}$	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. In Thailand, GAINS distinguishes five regions: Bangkok, Central Valley, Southern Peninsular, Northern Highlands, Northeast Plateau.

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 2015 provided by the Thailand Pollution Control Department, and observations for 2019 as contained in the WHO Ambient Air Quality Database. Only stations with temporal coverage >75% are used in the comparison. GAINS reproduces the variation of concentrations well but underestimates total $PM_{2.5}$ by approximately 40% on average, which can be due to underestimated emissions and missing sources, or lacking model resolution. Stations can be influenced by local sources such as busy roads and may reflect local conditions which GAINS cannot represent with its resolution of ~10km.

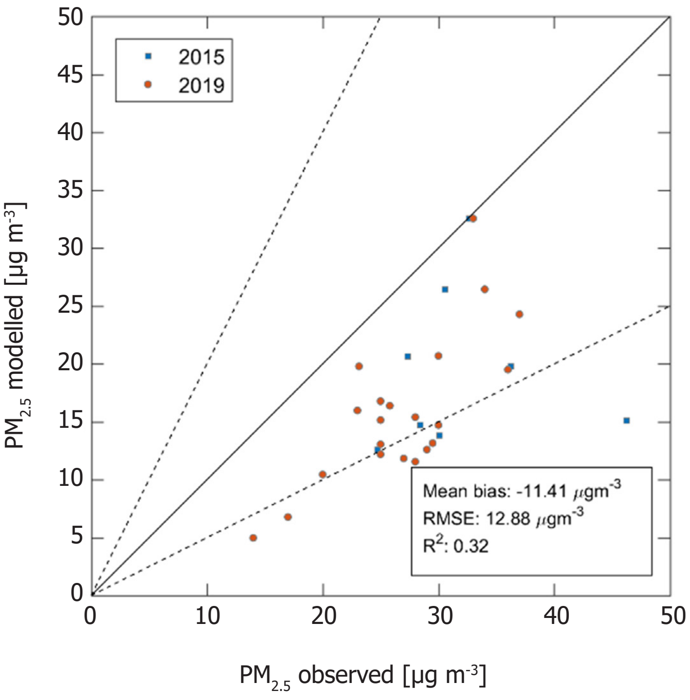

Fig 2. *Comparison of $PM_{2.5}$ concentrations modelled with GAINS for 2015 against observations in 2015 and 2019*

Concentration-response functions

Concentration-response functions (CRFs) used in this project have been derived from a systematic review and meta-analysis of recent epidemiological studies going beyond the evidence available to earlier assessments. Most existing CRFs for short-term exposures to $PM_{2.5}$ assume a fixed effect size in a log-linear function over an extrapolated exposure range, based on evidence primarily from Europe and North America, while the systematic review used for this assessment includes all available evidence globally. 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}

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 Global Burden of Disease Results Tool[2] 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 have been made available to this assessment by the Health Data Center (HDC), Ministry of Public Health. These have been used to calibrate the baseline morbidity levels in the assessment for the outcomes related to cardiovascular and respiratory hospital admissions. Only the primary diagnosis for hospital admission was taken into account.

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.

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[2] For more details, refer to: https://vizhub. healthdata.org/gbd-results.

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 Global Burden of Diseases 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 males and females from the GBD Results Tool[3] 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 (AHRQ, 2022) 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

The Report on Environmental Benefits Mapping and Analysis Program (BenMap) input data for Thailand (Pham, 2022) lists VSL estimated from studies conducted in Thailand. We use this value for VSL and estimated the Value of a Life Year (VOLY) by scaling the Thai VSL with the ratio of VOLY to VSL in the default data set.

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 the **Healthcare Cost and Utilization Project** (HCUPNet). As such, we had a unit cost dataset from 55 countries. We then obtained the Gross Domestic Product (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:

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

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

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[3] For more details, refer to: https://vizhub.healthdata.org/gbd-results.

Endpoint	Intercept	Slope
Children bronchitis symptom day	8.80	0.66
Children asthma symptom day	6.06	0.65
Adult bronchitis day	13.46	0.67
Work loss day	7.19	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 greenhouse gases 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 (NPS) and includes Nationally Determined Contributions (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, 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.

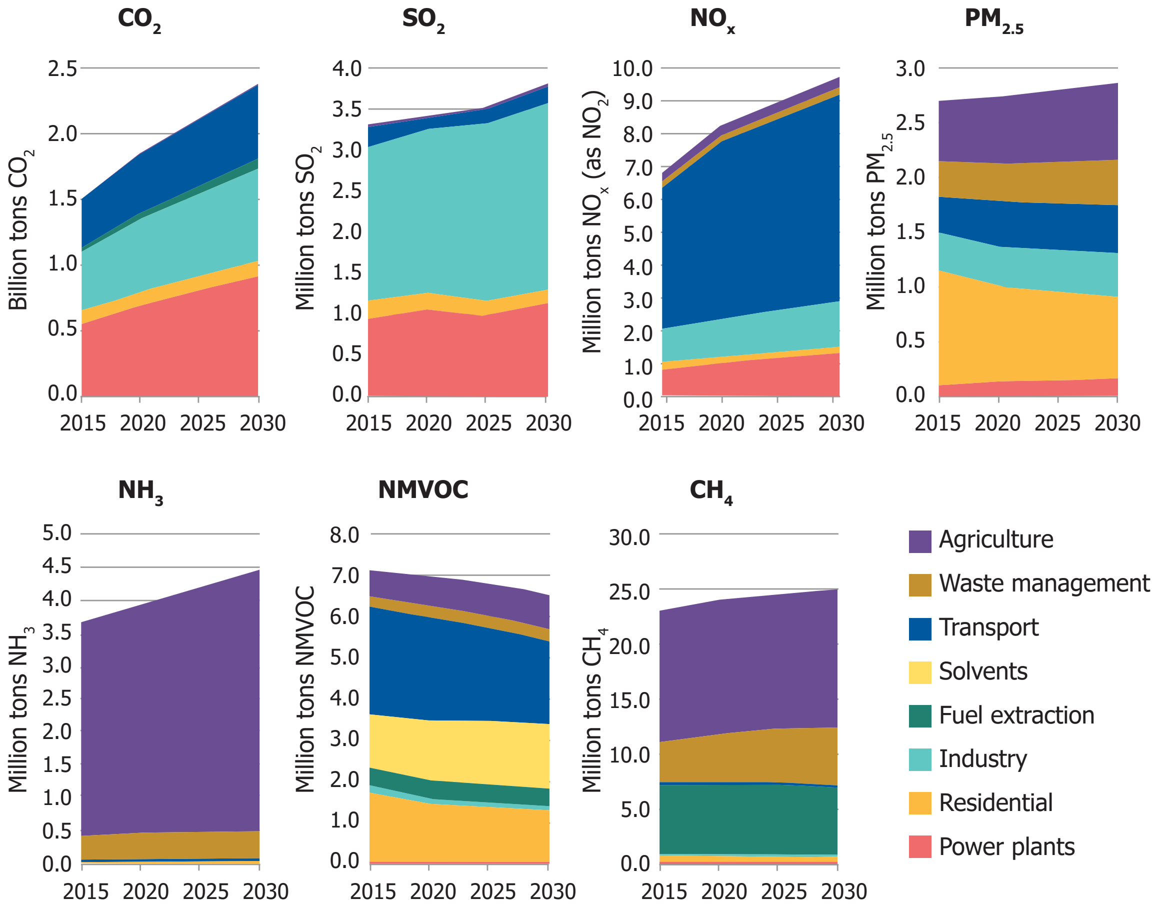

Fig 3. *Sectoral emissions of CO_2, primary $PM_{2.5}$, key precursors of ambient $PM_{2.5}$, and CH_4 for the ASEAN region in the Current Policies scenario*

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 International Energy Agency (IEA) NPS scenario and the Sustainable Development Scenario (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).

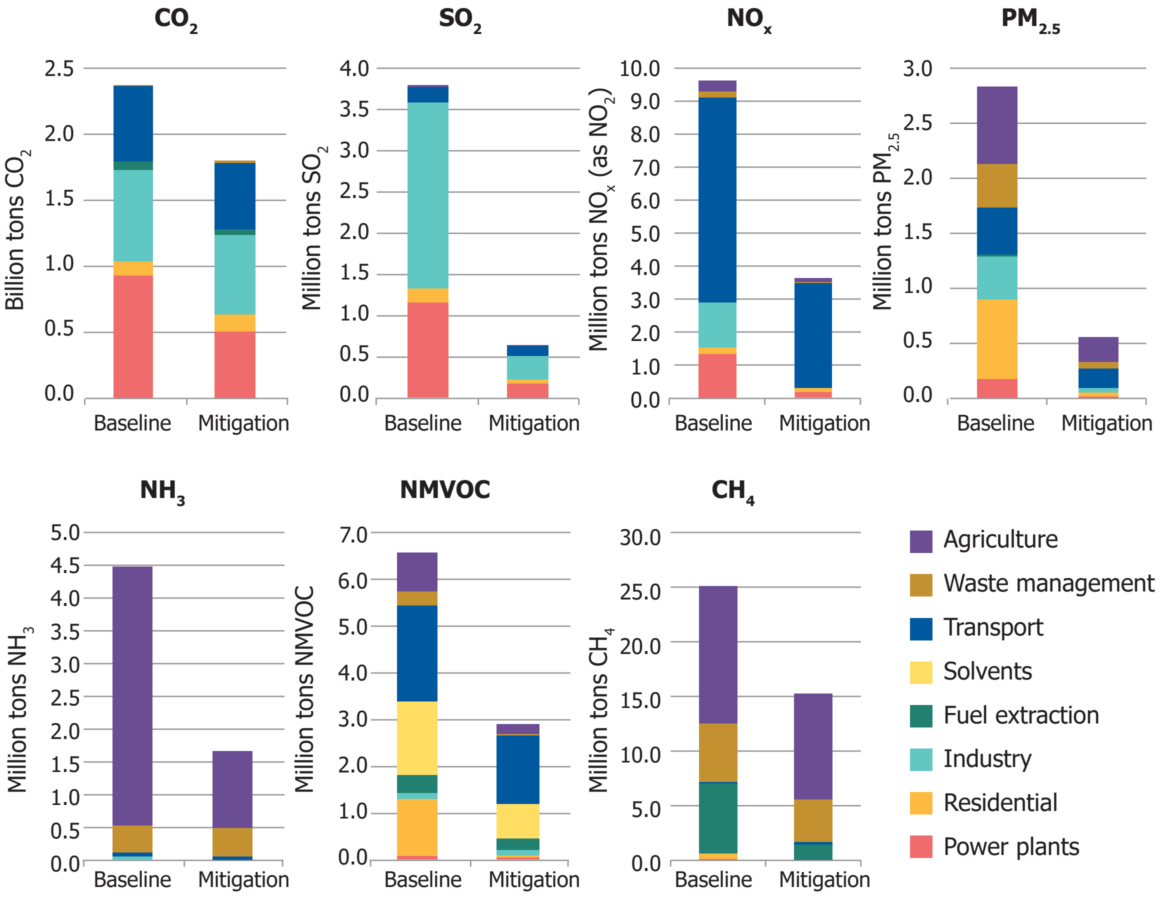

Fig 4. *Sectoral emissions of CO_2, primary $PM_{2.5}$, key precursors of ambient $PM_{2.5}$, and CH_4 for the ASEAN region in the Current Policies (Baseline) and Strong Mitigation scenario estimated for 2030*

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% (SO_2), and emissions of methane 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)[4] 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 $PM_{2.5}$. As shown in the national assessment report, several of these measures also bring strong co-benefits including reduction of greenhouse gases emissions and contribute to the achievement of several Sustainable Development Goals (SDGs).

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

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_x Reduction Selective Catalyst Reduction (deNO_x SCR) installations. Alternatively, flue gas desulfurization can be installed to achieve the same reduction of sulfur dioxide (SO_2) 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.
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.

REFERENCES

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

Chavanaves, S., Fantke, P., Limpaseni, W., Attavanich, W., Panyametheekul, S., Gheewala, S. H. et al. (2021). Health impacts and costs of fine particulate matter formation from road transport in Bangkok Metropolitan Region. *Atmospheric Pollution Research*, 12 (10), 101191, https://doi.org/10.1016/j.apr.2021.101191

Chulabhorn Research Institute. (2018). *Air Quality Assessments for Health and Environment Policies in Thailand, Chulabhorn Research Institute.*

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

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.

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

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

Nikam, J., Archer, D., & Nopsert, C. (2021). Regulating air quality in Thailand: Review of policies. *SEI Policy Brief*.

Pham T. (2022). *Technical note on Developing the BenMAP Database for Thai Health Burden Assessment*. Center for Clean Air Solution, Bangkok, Thailand.

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 (6), 7825–7865. https://doi.org/10.5194/acp-12-7825-2012

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.). Topics - *Efficiency and GHS Standards.* https://www.transportpolicy.net/topic/efficiency-and-ghg-standards/

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

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

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

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