COST-BENEFIT ANALYSIS FOR AIR POLLUTION CONTROL STRATEGIES IN JAKARTA

2024

COST-BENEFIT ANALYSIS FOR AIR POLLUTION CONTROL STRATEGIES IN JAKARTA

2024

This study is a result of a collaboration between
the Environmental Agency and the Health Agency of DKI Jakarta
and Vital Strategies, Institut Teknologi Nasional Bandung, and Universitas Padjadjaran
with the support from Bloomberg Philanthropies

Authors:
Dr. Eng. Didin Agustian Permadi, S.T., M.Eng.
Irlan Adiyatma Rum, ST., M.Sc.
apt. Ginanjar Syuhada, MSc.
Dr. Adiatma Yudistira Manogar Siregar, S.E., M.Econ.St.
Adhadian Akbar, S.E., MBA.
Donny Hardiawan, S.E., M.E.
Chintya Imelda Maidir, MPP.

Study Advisor:
Sumi Mehta, MPH, Ph.D.

Suggested citation:
Permadi D *et al*. Cost-benefit Analysis for Air Pollution Control Strategies in Jakarta. Vital Strategies, New York NY. 2024. Available at: www.vitalstrategies.org/resources/cost-benefit-analysis-for-air-pollution-control-strategies-in-jakarta/

Table of Contents

LIST OF ABBREVIATIONS

AERMOD	American Meteorology Society Environmental Protection Agency Regulatory Model
BAU	Business-as-usual scenario
BPJS	Healthcare and Social Security Agency
BPS	Indonesia Central Bureau of Statistics
EV	Electric vehicle
ICD-10	International Classification of Diseases 10th Revision
IDR	Indonesian Rupiah
INHI	Indonesian National Health Insurance
KDO	Government Operational Vehicle
KRL	Greater Jakarta commuter rail
LPG	Liquefied petroleum gas
MR-BRT	Meta Regression – Bayesian, Regularized, Trimmed
NAAQS	National Ambient Air Quality Standard
$PM_{2.5}$	Particulate matter 2.5 micrometers or less in aerodynamic diameter
PM_{10}	Particulate matter 10 micrometers or less in aerodynamic diameter
RED	Reduction scenario
RR	Relative risk
VSL	Value of statistical life
WHO	World Health Organization

EXECUTIVE SUMMARY

Several measures have been identified to achieve emission-reduction targets as mandated by the Grand Design for Air Pollution Control of Jakarta Province for the year 2030. Five measures are related to mobile sources, while the other three are related to area sources: residential, construction and municipal solid waste open burning. Integrated emission inventory and modeling are employed to analyze the efficacy of each measure on emission reduction and $PM_{2.5}$ air quality improvement. The results show the highest efficacies obtained for emission-standard compliance and shifting to public transport, respectively.

For all measures relevant to mobile sources, $PM_{2.5}$ air quality improvement ranges from 0.5 to 5.7 µg/m^3 while emission reductions for area sources yield of 0.05-2.4 µg/m^3 (maximum annual average). Domain average concentrations of $PM_{2.5}$ improvement are within the range of 0.13-1.5 µg/m^3 (mobile sources relevant measures) and 0.01-0.7 µg/m^3 (area sources relevant measures). Collective implementation of all the measures in 2030 will help to anticipate increasing $PM_{2.5}$ concentrations compared to the levels measured in 2019. More aggressive measures are still required to bring down the $PM_{2.5}$ annual average levels below the National Ambient Air Quality Standards (NAAQS) of 15 µg/m^3.

We estimate that the overall cost of all programs is IDR86.5 trillion, or approximately 3.1% of Jakarta's GDRP. Shifting to public transportation, emission testing for private vehicles and the household energy shift program accounts for 56.5%, 21.2% and 8.4% of the total cost respectively. These numbers are proportionate to the total number of impacted users. These results, however, are subject to the target that DKI Jakarta has set up and the assumption that underlies the calculation. Some predictions were made using different trends based on the nature of the data using a 2019 base year.

$PM_{2.5}$-related health outcomes were estimated using methodology used in the Global Burden of Disease Study 2019 and the most recent concentration-response functions. Historical data obtained from previous national health reports were used to project prevalence rates in the future. We find that, in total, more than 32,000 cause-specific deaths, almost 300 infant deaths, more than 12,000 stunting cases and more than 2,000 adverse birth conditions can be averted if the listed strategies to control air pollution can be implemented in Jakarta. Note that we do not include acute health conditions, such as respiratory symptoms, in analyses due to the limitations in emission data and scientific

evidence available. This may underestimate the health benefits of air pollution control strategies.

Given the health outcomes, this study finds that the total benefit of all interventions amounts to IDR643 trillion (US$45.5 billion, using IDR14,136 per US$1), reaching 23% of Jakarta province GDRP. The largest benefit comes from emission testing (sharing approximately 32% of the total benefit at around IDR203 trillion), followed by shifting to public transportation (25%, IDR162 trillion).

Note that our results may undervalue the total benefit. For instance, our estimate of the benefit of averting cases of stunting only reflects the benefit of avoiding the costs of treating the condition. We did not calculate the potential benefit of avoiding future productivity loss, as we feel that there would be too many uncertainties for such an estimate. Regardless, this is an important factor that needs to be considered when making pollution control policies, as we have shown that avoiding stunting is a part of the benefit of pollution control interventions.

INTRODUCTION

The Grand Design for Air Pollution Control has been formulated to help combat Jakarta's urgent air pollution problem. Targets have been established to improve air quality and public health, as well as other efforts to provide science-based evidence for air quality management. There is a need to further evaluate the beneficial impacts of measure implementation, which can be done through cost-benefit analysis. This concept was implemented long ago in the United States to analyze the cost-effectiveness and cost-benefit of air quality regulations [1]. The framework is also useful to set targets for improvement of air pollution control policy in Europe [2] or in Asia [3], [4]. The use of cost-benefit analysis in air pollution control policy design becomes crucial especially to help policymakers prioritize measures [5]. Nowadays, countries better realize the important role of cost-benefit analysis as part of the air quality management component, even at the city level [6].

Information on air pollutant emission sources in Jakarta gathered through emission inventory study is crucial as a starting point for this analysis. This approach has been widely used to account for the real costs and benefits of environmental policies by quantifying their air pollution effects. For policymakers, this information is useful for preliminary evaluation of decision-making for emission-reduction measures. In general, this study consists of three important components for estimating benefits and costs of air pollution control measures for Jakarta: i) impacts of measures on air pollution, ii) benefits of air quality improvement and iii) costs of controls. Selected measures were scrutinized and the associated impacts on emission were estimated in the previous study [7], to be compared with the no-control emission. An air quality dispersion model was employed to estimate impacts of emission reductions on air quality before the interventions are implemented (ex ante air quality). The improvement of air quality (especially $PM_{2.5}$) was then linked to the potential health benefits. The result was then monetized to show the avoided actual medical expenses. The value was then compared with that estimated for the costs of programs/measures. The cost-benefit analysis results also provide a ranking of measures in terms of magnitude of cost-benefit ratio.

METHODS

Modeling of Air Quality Impacts of Emission Scenarios

The impact of emission scenarios on air quality over Jakarta Province was assessed using an air quality modeling approach. This approach is useful to link the emission reduction or increase to the associated air quality improvement or deterioration in the study area. We used the American Meteorology Society Environmental Protection Agency Regulatory Model (AERMOD)/AERMET, the United States Environmental Protection Agency's (US EPA) preferred dispersion model, to simulate impacts of emission scenarios. AERMOD is an air quality spatial dispersion model intended for compliance with regulations and can predict the distribution of air quality from up to 50 different sources (point, area, or volume sources); besides that, the distribution of air quality from mobile sources can also be predicted by this software [8]. The selected models can efficiently simulate many cases in a relatively affordable computing resource. Figure 1 describes the general framework for impact modeling of the emission scenarios on air quality in DKI Jakarta province.

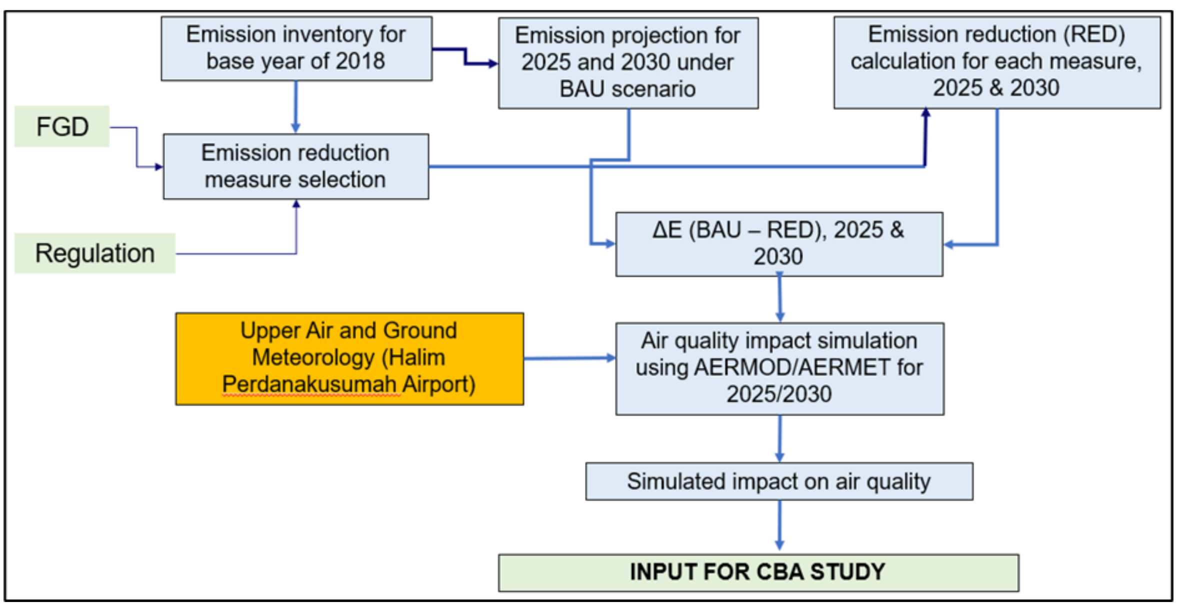


Figure 1. General framework for the modeling of air quality impacts of emission scenarios. Note: Focus Group Discussion, BAU = Business as Usual

Base-year emission inventory data for trace gases (i.e., NOx, SO_2, CO, VOC) and particulate matter (PM) (i.e., PM_{10}, $PM_{2.5}$, black carbon, organic carbon) were taken from online resources [7], [9] with updates on missing sources, e.g., solid waste open burning, VOC evaporation from fuel station, etc. Two emission scenarios were developed previously for the time horizon of 2030—business as usual (BAU) and emission reduction (RED)—and details on methodology were included in the report. The RED scenario reflected some measures that have been planned by the provincial government of DKI Jakarta and are relevant to emission reductions of air pollutants. Input and recommendations were also incorporated from suggestions put forth during public focus-group discussions held by provincial governments. Further, emission reductions for target pollutants (i.e., $PM_{2.5}$ and gas precursors of NOx and SO_2) were calculated and transformed to the model-ready input format.

Implications of emission reductions on air quality improvement were then simulated using the AERMOD/AERMET model for the years 2025 and 2030, the times when the measures will be implemented with specific achievement targets. We calculated emission reductions using the following equation:

$$\text{(Eq.1) } EM_{red} = EM_{BAU2025,2030} - EM_{RED2025,2030}$$

Where:

EM_{red}	: Emission reduction in 2025 and 2030 in ton/year
$EM_{BAU2025,2030}$	: Emission projection under BAU scenario for 2025 and 2030 in ton/year
$EM_{RED2025,2030}$	: Emission when the certain measure is being implemented in 2025 and 2030 in ton/year

Emission reductions for each measure for $PM_{2.5}$, NOx and SO_2 were calculated, and spatial distributions were developed in order to be simulated using AERMOD/AERMET. Results of annual average concentrations in terms of domain average and maximum value were then used for the cost-benefit analysis.

Business-as-usual (BAU) scenario

The business-as-usual (BAU) emission scenario considers current legislation and historical trends of past emission sources related to activity data in the province. The projected year is 2030 (with an interim year of 2025), as guided in the Grand Design for Air Pollution Control document. More detail on methodology and calculation is presented elsewhere [7]. Emission sources relevant activity data for 10 years (2008-2018) has been collected, and the summary of historical trends is presented in Table 5. Gas fuel consumption in power generation is projected to increase by an annual average of 14.9% for the two large power plants located in the northern part of Jakarta. High-speed diesel fuel consumption in power generation shows a decreasing trend, and it will end by 2025. The historical trends of registered vehicles in DKI Jakarta show the highest annual increase rates for trucks, motorcycles and passenger cars at 11%, 11%, and 3.2% respectively. The trends of annual increasing rates for other sources also show an increasing pattern, as shown in Table 1.

Table 1 Future changes of emission sources relevant activity data in Jakarta

Emission source	**Activity data**	**Historical trends**
I. Fuel combustion in energy sector		
Energy industry	Fuel consumption	Gas: +14.9%; MFO: -9.7%; HSD: -9.8%
Manufacturing industry	Fuel consumption	Diesel oil: -2.6%; gasoline: -4.8%; gas and coal were also used in 2019
Transportation		
On-road	Number of registered vehicles	MC: +11%; PC: +3.2%; truck: 11%; Other: +2.3%
Aviation	Landing and takeoff	International: +2.9%; domestic: +18.8%
Marine transport	Ship call	+1.2%
Commercial	Gross regional income for commercial sector	+3.5%
Residential	LPG consumption	+1%
II. Non-combustion		
Construction	Construction index	+ 2.1%
Fugitive emission*	Fuel sale	+3.2%
Solid waste open burning*	Population	+1%

Note: HSD = high-speed diesel oil, MC = motorcycle, PC = passenger car.

Source: LPPM Itenas and Vital Strategies (2022) [7]

Reduction (RED) scenarios

In the reduction (RED) scenario, measures that create emission reductions and relevant information on target of implementation and brief calculation methodology are selected, as listed in Table 2. Measure screening was done by collecting information on policy documents, further shortlisted through a focus-group discussion with the provincial government working unit. The working unit provided input and suggestions on the measures that will be implemented under their authority.

Table 2 Brief description on selected emission reduction measures

Code	Description	Target	Calculation
OTR1	Governmental operational electric vehicle (all fleet)	100% in 2025 and 2030	$E = N_{KDO}$ x VKT x EF (BAU – RED)
OTR2	Stringent emission standard for microbus to comply with Euro 4	100% in 2025 and 2030	$E = N_{micro}$ x VKT x EF (BAU – RED)
OTR3	Transjakarta electric buses (annual addition of unit)	160 in 2025 and 200 in 2030	$E = N_{bus}$ x VKT x EF_{WTW} (BAU – RED)
OTR4	Regular emission testing (target to comply at least Euro 2)	50% (2025) 100% (2030) for PC & MC	$E = N_{PC,MC}$ x VKT x $EF_{PC,MC}$ (BAU – RED)
OTR5	Shifting to public transportation	30% (2025) 60% (2030) for private fleet	
RES	Conversion from LPG stove to electric stove	1,9% (2025) 10% (2030) of household	E = Fuel Consumption x EF
DUST	Dust control from construction activity	100% (both 2025 & 2030)	`C = 100 – ((0.8 x p x d x t)/i)
OB	Ban of municipal solid waste open burning	100% (both 2025 & 2030)	$Ms = Pc \times P_{frac} \times MSW_{GR} \times \delta \times \eta \times 365$

Note: Detail calculation methodology can be seen in Vital Strategies and LPPM Itenas (2022). VKT = vehicle kilometers traveled, EF = emission factor, N = number of registered vehicles, C = construction duct removal efficiency, p = daily evaporation rate, d = hour operation of transport, i = water spraying intensity, Pc = population, P_{frac} = fraction of population burning waste, MSW_{GR} = municipal solid waste generation factor, δ = fraction of combustible waste, η = combustion efficiency.

Modeling spatial distribution of emissions

AERMOD requires spatial distribution of emission input data, which can be expressed as either line, point or area sources. We considered measures of on-road transport as line sources (OTR1-OTR5) while others were considered as area sources

(RES, DUST and OB). For line sources, emissions were allocated along the major road networks, while for area sources, emissions were distributed into 2 x 2 km^2 grids. Spatial distribution of emissions for each measure were done using specific proxies as presented in Table 3.

Table 3 Proxies used for spatial distribution of emission reduction measures

Code	Measures	Type of proxies
OTR1	Government operational electric vehicles (all fleet)	Road length and traffic volume
OTR2	Stringent emission standard for microbus to comply with Euro 4	Route of microbus
OTR3	Transjakarta electric buses (annual addition of unit)	Route of Transjakarta buses
OTR4	Regular emission testing (target to comply with at least Euro 2)	Road length and traffic volume
OTR5	Shifting to public transportation	Road length and traffic volume
RES	Conversion from LPG stove to electric stove	Population density
DUST	Dust control from construction activity	Built areas based on land use map
OB	Ban of municipal solid waste open burning	Population density

Costs for Implementing Air Pollution Control Strategies in Jakarta

The government of Jakarta determines program interventions and impact targets, which provide a clear view of the roadmap for reducing air pollution in Jakarta and are the basis for assessing the economic costs of program interventions for Jakarta's economy. The costs are subject to the scope of the program activity. From direct to indirect costs, many of these are beyond the scope of this study. Instead, this chapter focuses on what the government budget has planned thus far, including subsidising public transport ticket prices and promoting cleaner fuel use to tackle air pollution.

Framework for estimating cost of programs

To estimate the cost of programs, methods to calculate the economic costs of each program were determined. There are five methods to calculate the economic costs, which are briefly explained below:

- Expert judgement: It relies on the knowledge and experience of professionals, and the outcomes may vary among different experts.
- Analogous estimating: It is based on the value of previous similar programs using adoption and adjustment. The cost will be estimated by the program.
- Parametric estimating: It uses the historic cost per parameter unit from previous similar programs to determine the expected cost of the current program.
- Bottom-up estimating: It is based on the estimation of expected costs at the activity level and aggregates the costs required for the whole program.
- Three-point estimating: It combines analogous, parametric or bottom-up estimating to get the refined cost estimate.

In this study, we used three types of estimation—analogous, parametric and bottom-up—to calculate the economic costs of each program intervention, as shown in Figure 2. We estimated the base-year economic costs in this study because of their importance in the benefit-cost comparison.

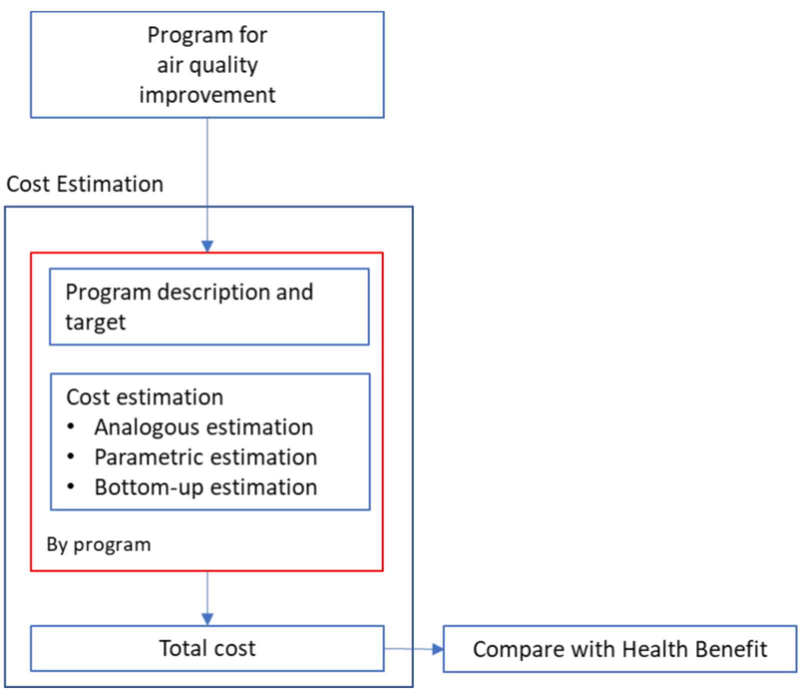


Figure 2. Analysis framework for estimating cost of interventions.

We used targets specified in the GDPPU for each program intervention. The target units are in percentage and specific units, depending on the programs. We used a 12-year period (from 2019 to 2030) to estimate the cost of intervention. The costs were calculated on an annual basis with 2018 as the base year. We identified costs from several sources including capital cost, cost of subsidy and recurrent cost. The capital cost consists of expenses incurred via the purchase of equipment, buildings and infrastructure to implement the air quality improvement program. The cost of subsidy is a proxy to calculate how much social cost is needed to implement the program. The recurrent cost is the annual cost of the government's budget planning.

Table 4 List of interventions and the targets set

Code - Intervention program	Cost	Target year	Target unit	Estimated target unit	Target trend (full/missing)
OTR1 - Government operational electric vehicles (EV)	Capital cost	Annual target 2022-2030	From 70 % by 2022 to 100% in 2025, and steady 100% until 2030	From 40% in 2019 to 60% in 2021	Gradual (full)
OTR2 - Stringent emission standard for microbus to comply Euro 4	Capital cost, cost of subsidy	Annual target 2022-2030	From 20% by 2022 to 100% in 2025, and steady 100% until 2030	From 5% in 2019 to 15% in 2021	Gradual (full)
OTR3 – Transjakarta electric buses	Capital cost	Annual target 2022-2030	40 unit per year starting 2022	40 unit per year starting 2019	Gradual (full)
OTR4 - Emission test for private vehicles	Recurrent cost	Annual target 2022-2030	From 20% by 2022 to 100% in 2026, and steady 100% until 2030	From 5% in 2019 to 15% in 2021	Gradual (full)

OTR5 - Shifting to public transportation	Capital cost, cost of subsidy	Year target 2025 and 2030	30% in 2025 and 60% in 2030	From 13.1% in 2019 to 17.2% in 2021, 30% in 2025, 60% in 2030	Estimation (missing)
RES - Conversion from LPG stove to electric stove	Capital cost, cost of subsidy	Year target 2024 and 2030	1.9% in 2024 and 10% in 2030	From 0.48% in 2019 to 1.44% in 2023, 1.9% in 2024, 2.5% in 2025, 10% in 2030	Missing (estimation)
DUST - Dust control from construction activity	Recurrent cost	Annual target 2022-2030	100% from 2022	Similar	Full (static)
OB - Ban of municipal solid waste open burning	Recurrent cost	Annual target 2024-2030	100% from 2024	Similar	Full (static)

In general, the initial target is a cumulative target for 2022 to 2030. For 2019 to 2021, we estimated the target using the trend from 2022 to 2030. From Table 4, we identified the source of cost for each program intervention. For transportation related programs:

- OTR1 used capital cost, with a cumulative target in percentage, and the target gradually increases until 2025; electric vehicles were procured during the period; different operational costs exist between gas and electric vehicles.
- OTR2 used capital cost and cost of subsidy, with a cumulative target in percentage, and the target gradually increased until 2025; the number of microbuses and public transportation in Transjakarta was projected; the total demand for solar and the difference in price between subsidized solar and Euro 4 solar each year were calculated; the emission test for public vehicles was also considered.

- OTR3 used capital cost, with an annual target unit in the number of vehicles, and a constant target until 2030; the electric public bus was procured during the period; the maintenance cost for public buses was considered.
- OTR4 used recurrent costs with a cumulative target in percentage, and the target gradually increased until 2026; the numbers of private vehicles, cars, and motorcycles were projected; operational costs were calculated for emission tests on private vehicles; procurement costs for emission test units and their maintenance costs were considered.
- OTR5 used capital cost and cost of subsidy, with a cumulative target in percentage, and a specific target for a certain year; the number of people using private vehicles and the number of people shifting to public transport were projected; operational and maintenance costs for public buses, Transjakarta and Jakarta commuter rail were projected.

For non-transportation related programs:

- RES used capital cost and cost of subsidy, with a cumulative target in percentage, and a specific target for a certain year; the number of households in Jakarta was projected for each year; the total cost of conversion to an electric stove was calculated; maintenance costs were considered.
- DUST used recurrent cost, with an annual target in percentage and with a constant target; operational and maintenance costs for environmental impact were calculated; the number of firms was projected.
- OB used recurrent costs with a constant target; the projected number of households in Jakarta was used; operational and monitoring costs were calculated.

Data collection

In this study, we collected both main and supporting data from several sources. The main data was taken from official data publications, while supporting data was from public information. Some official sources include data publication from: i) government regulation, both at national and provincial level; ii) Ministry of Energy and Mineral Resources; iii) Indonesian Statistics Office, both at the national and provincial level; iv) provincial environmental agencies; v) provincial transportation agencies; and vi) Indonesian Railway

Company. We also extracted information form publicly available sources, such as online national news sites, to obtain additional supporting information.

For the overall program activities, we referred to the Grand Design for Air Pollution Control initiative from the government of DKI Jakarta in 2022. For the government electric vehicle program, we referred to the Presidential Instruction No. 7/2022 on the use of electric vehicles at government institutions. According to the regulation, the government of DKI Jakarta is obliged to set up regulations and budget allocations to accelerate the implementation of electric vehicles as government operational service vehicles. We collected data on the number of government operational vehicles in DKI Jakarta from the city government's public data website. We estimated the number of vehicles in Indonesia based on previous official data provided by the city statistics office. The increase in government vehicles was proportional to the number of civil servants in DKI Jakarta.

For programs related to public transportation, we used government subsidies based on solar consumption data by sector and province provided by the Ministry of Energy and Mineral Resources. Data on transportation quantity, such as the number of vehicles in DKI Jakarta, was extracted from the 2016-2021 transportation statistics provided by the city statistics office. Retribution rates for emission testing and the integration tariff for all public transportation were obtained from the Transportation Agency in DKI Jakarta.

For programs related to households, we estimated the number of households in DKI Jakarta from previous data provided by the Statistics Office. We also referred to the program and budgeting of the Environmental Agency of DKI Jakarta related to the air quality improvement initiatives. We referred to program planning and budgeting designed by the Indonesian Railway Company to calculate transportation costs by public trains. Information about the number of government vehicles to be procured and electric public buses was taken from government news, national online news sites, and official reports from relevant organizations.

Assumptions used to estimate cost of programs

We made some clear assumptions in this study for each program, as explained below. These assumptions are further described in Supplementary 1.

- OTR1. We assumed the number of government electric vehicles for motorcycles in 2023 to be 110 units for IDR4.4 billion. The number of government vehicles in DKI Jakarta in 2015 was 332 units (139 cars and 183 motorcycles). The annual growth rate for government vehicles is 0.5% for cars and 1% for motorcycles. The projected trend for government vehicles is assumed to be linear. The price of an EV car in 2023 will be IDR299.5 million, and the price of an EV motorcycle will be IDR10.3 million. The operational cost per conventional government vehicle is IDR5 million, while the cost per EV is IDR10 million.

- OTR2. We take the number of public transportation units (bus and microbus) in 2019 to be 35,602 units in DKI Jakarta. The growth rate of public transport is -8.12%, according to the 2016-2019 data. We assumed that the negative growth rate will reach steady-state growth in 2025, when the optimum number of public transports has been reached. The projected trend for public transport is linear. The price of solar Dexlite CN51 is IDR17,100, and the price of BioSolar CN48 is IDR6,800. The share of DKI in national consumption of solar use is 15%, and the share of public transport in the total transportation sector is 10%. The total demand for solar at the national level is assumed to reach 14.79 million liters. We assumed that the growth in oil prices would be approximately 10%. The price of an emission test for public transport is IDR87,000 per vehicle. We also assumed that, in 2025, the number of public transports might reach its optimal number, where the marginal cost is equal to the marginal revenue (MC=MR).
- OTR3. We take the price of an electric bus to be around IDR5 billion per unit. The projected trend for the total electric bus is to be linear. The rate of maintenance is 7.5% of the total annual costs.
- OTR4. The number of private vehicles in 2019 reached 2,805,989 units of cars and 8,194,590 units of motorcycles. The projected trend in the number of private vehicles is assumed to be linear. The growth of private vehicles is assumed to reach 2.59% for cars and 4.11% for motorcycles. The unit operational cost of an emission test is around IDR127,764 per vehicle. The operational cost is the cost of resources used by the government to operate emissions test programs for private vehicles in DKI Jakarta. The equipment for testing emissions is procured every 3 years. The rate of maintenance is 7.5% of the total annual costs.
- OTR5. We define public transport as trains and buses. The number of passengers in a car is two, and for a motorcycle it is one. The transportation cost per day for KRL/Transjakarta is assumed to be IDR10,000. The coverage for subsidies starts at 50% of the total people shifting in the early period to 25% at the end period. The

projection trend for the number of people shifting to public transport is assumed to be exponential, while the projection trend for KRL and Transjakarta passengers is logarithmic. The growth of total revenue at RKL is 15.88%, and the growth of total revenue at Transjakarta is 28.88%. The share of operational costs in the total revenue of KRL/Transjakarta is 80%. The rate of maintenance is 7.5% of the total annual operational costs.

- RES. The number of households in 2021 has been estimated to be 2,770,729 people. The projection for the number of households follows an exponential trend. The subsidy for electric stoves per household is assumed to be IDR2.5 million, including operational costs (procurement, installation and socialization). The maintenance rate is 7.5% of the total annual operational costs.
- DUS. The budget for controlling the program in 2022 was IDR256.65 million, and the total number of firms in DKI Jakarta in 2020 was 1,721 units. The operational cost per unit firm is around 10%, and the maintenance rate is 7.5% of the total annual operational cost.
- OB. The budget for controlling the program in 2022 was IDR544.67 million. The total number of households per cluster was 1,000. The operational cost per cluster is around 16 million IDR, and the maintenance rate is 7.5% of the total annual costs.

Calculating cost of programs

OTR1: Government operational electric vehicles program

This program aims to procure new government operational service vehicles (known as KDOs) to gradually replace gasoline-fueled KDOs. The DKI Statistics Office (later called the BPS) reports the annual transportation statistics for all types of vehicles. BPS shows that the annual growth of vehicles in DKI Jakarta is 4.4% [10]. The government of DKI Jakarta has allocated IDR4.4 billion for 110 units of EV motorcycles in its 2023 budget planning [11]. The unit-price estimation will be IDR40 million for an EV motorcycle and IDR1 billion for an EV car [12]. By 2022, The government imposed a target of 70% of the KDOs to be powered by electricity. Full EV implementation for KDOs will be targeted from 2025 to 2030 [13]. We set interim targets for 2019-2021 from 40 to 60%, assuming a 10% increase every year. From these targets, we calculated the number of EVs to procure in each year and multiplied the numbers with unit prices. To obtain the total cost for this program, we summed up all costs coming from procurement, maintenance and operational processes.

OTR2: Stringent emission standard for microbus to comply with Euro 4

This program aims to impose an emission standard according to the Euro 4 emissions standard for microbus and non-Transjakarta public transportation (later they will be referred to as public transport). A target was set that 20% of public transport should meet the standards by 2022. To pass the standards, the N_2O content in gasoline vehicles may not exceed 80 milligrams per kilometer, 250 milligrams per kilometer for diesel vehicles and 25 milligram per kilometer for diesel particulate matter (PM). To meet these requirements, two important factors determine the process: fuel quality and vehicle engine quality. Almost all national automotive manufactures have adopted technologies that produce engines that meet the Euro 4 emissions standard. Thus, the way in which public transport switches to better fuels to meet the standard is also important.

BPS published annual data on microbuses and public transportation in DKI Jakarta [12], [14]. Public transport includes large, medium and small buses, small feeder buses and intercity buses. According to the reports, there were 45,900 units in 2016 and 35,600 units in 2019, meaning that the number of public transportation vehicles in DKI Jakarta decreased by 8.12% per year. To project the total numbers of public transport available in the respective year, we used a linear trend. From these numbers, we calculated total public transport compliance with Euro 4 standards according to the annual target listed in Table 4.

Based on data from the Ministry of Energy and Mineral Resources [15], the total diesel consumption in Indonesia was estimated at 1.59 million kiloliters in 2021. According to this data, the total use of diesel in the industry sector was 571,000 kiloliters, while the transportation sector used 933,600 kiloliters of diesel, or 62% of the total diesel consumption (in this study, we use 60%). Using the interval from 2011 to 2018, the average subsidized diesel consumption in Indonesia is around 14.7 million liters/year. Based on BPS [16], the number of vehicles in DKI Jakarta in 2021 is estimated at about 21.8 million units, or 15% of nationwide total vehicles. Another data source from BPS also shows the total number of public transportation vehicles compared to total vehicles in DKI Jakarta, which is around 10% [14]. From this information, we estimated the annual use of diesel for public transport in DKI Jakarta at around 133.1 million liters, or 3,700 liters per unit.

The public transport sector may not be interested in switching to better fuel soon, as their current marginal cost is higher than their marginal benefit from using fuel at a higher price. There are two types of fuel sold by Pertamina, namely Pertamina Dex and Dexlite. To meet the Euro 4 standard, Dexlite CN51 should be used, considering that the price per liter is lower than Pertamina Dex and has CN 51 (higher than subsidized diesel fuel called BioSolar). The price of Dexlite CN51 is IDR17,100/liter. To allow the transition for public transport to consume Dexlite CN51, subsidy support from the government is needed. The standard price for acceptable gasoline is a maximum of IDR6,800/liter, which is the price of BioSolar, commonly used by public transport. Thus, the minimum amount of subsidy that needs to be prepared by the government is IDR10,300/liter (60% of the retail price).

We calculated the total cost by estimating the potential subsidies to public transport to allow them to consume better fuel. The total numbers of public transportation vehicles complying with Euro 4 standards in the respective year were multiplied by the annual diesel consumption and the amount of diesel subsidy required per liter. The final results of the calculation were summed to obtain the total cost to implement the OTR2 program.

OTR3: Transjakarta electric buses

The public electric bus program aims to increase the number of electric non-micro Transjakarta buses in DKI Jakarta. The program targeted 40 units of Transjakarta electric buses to be available by 2022, which increases to 360 units of electric buses by 2030. The price for one unit of electric bus is estimated to be IDR5 billion [17]. Operational costs would be the total procurement cost for electric buses in the respective year. To keep these electric buses functioning optimally, 7.5% of the annual operational costs were required as maintenance costs. The total cost to implement this program was calculated by totaling the operational costs and maintenance costs.

OTR4: Emission test for private vehicles

The aim of this program is to implement emission tests for private vehicles on a regular basis. By 2022, 20% of private vehicles were targeted to fulfill the emission standards set by DKI Jakarta. Based on BPS data [18], the number of private motorcycles in DKI Jakarta was 14.1 million units in 2017 and 16.5 million units in 2021. The number of private cars in 2017 and 2021 was around 3.7 and 4.1 million units, respectively. The annual growth of private vehicles will be 4.1% for motorcycles and 2.59% for cars. We estimated the number of private vehicles for 2022-2030 using a linear trend.

Based on government budgeting for 2022 in DKI Jakarta [14], the operational budget for emission testing is around IDR76 million and the procurement budget for emission test equipment is around IDR1.2 billion. We assume that these budgets are for road transportation using private vehicles only. According to their Information System for Emissions Test, only 550,800 private cars and 49,700 private motorcycles have been tested for emissions in 2022 (this differs from the targeted numbers in Figure 6). Using this information, the operational cost per unit vehicle is approximately IDR127,700. Besides the operational and procurement budget, we also consider maintenance cost. The annual cost of maintenance was estimated to be 7.5% of the annual operational cost. We calculated the total cost to implement the emission testing program in DKI Jakarta by summing operational and maintenance costs, then multiplying them by the total number of private vehicles targeted to have their emissions tested.

OTR5: Shifting to public transportation

The program aims to reduce the use of private vehicles and increase the use of public transportation in DKI Jakarta. According to BPS data [18], the number of private vehicles in 2021 was 4.1 million cars and 16.5 million motorcycles. The program has targeted that 30% of the number of private passengers will shift to public transport by 2025. This percentage will increase to 60% in 2030. A linear assumption was used to estimate the number of private passengers shifting to public transport.

To shift the private passengers to public transport, a subsidy program was required. We estimated the total subsidy by calculating the willingness to pay for using public transport according to the daily maximum integrated tariff for buses issued by DKI Jakarta [19]. We assumed that only half of private passengers will receive the subsidy by 2022, which gradually decreases to 25% by 2030.

Apart from the subsidy to change people’s behavior and encourage them switch to public transport, this transition will increase the operational costs due to the greater number of passengers. Therefore, the operational costs per passenger should be determined. The annual operational costs were obtained from annual reports of Transjakarta [20] and Indonesian railways [21]. Total numbers of public transport passengers were obtained from

BPS [12], [14], [22]. A logarithmic trend was used to estimate the numbers of public transport passengers in 2020-2030.

Total implementation costs for this program consist of total subsidy provided by the government, total operational costs, and total maintenance costs spent by public transport providers.

RES: Conversion from LPG stove to electric stove

This program aims to reduce the use of LPG stoves and increase the use of electric stoves in households in the DKI Jakarta urban area, with a target of around 1.9% of households switching to electric stoves by 2024 and 10% of the households by 2030. Based on the BPS data [23], the number of households in DKI Jakarta in 2020 and 2021 reached 2.7 million. From this data we projected the number of households up to 2030 using an exponential trend. Then we calculated the total number of households targeted to use electric stoves according to the annual target of this program.

Therefore, the overall implementation cost for this program was the multiplication result of subsidy provided and total target households in the respective years, plus the annual maintenance costs. To ensure the program can be implemented successfully, a subsidy program for electric stoves should be provided by the government.

DUST: Dust control from construction activity

The program aims to implement emission standards for construction activity in DKI Jakarta. It is targeted that this control process will succeed in achieving the 100% target each year, as shown in Table 4. The DKI Jakarta Environment Agency had a budget of around IDR241 million in 2021 and IDR256 million in 2022 for monitoring the implementation of the environmental monitoring program [24]. We used these numbers to project the monitoring cost in upcoming years using linear trends.

OB: Ban of municipal solid waste open burning

The program aims to control household waste and prohibit open burning in DKI Jakarta and is expected to achieve 100% targets by 2025. The budget prepared by DKI Jakarta was IDR472 million in 2021 and IDR544 million in 2022 [24]. This budget includes controlling single-use plastic waste, monitoring household waste, and facilitating waste banks in DKI Jakarta. Linear trends were used to estimate the budget needed in 2023-2030.

Assessment of Health Benefits

Baseline data

We included long-term (chronic) health effects of air pollution, i.e., cause-specific mortality (due to ischemic heart disease, stroke, chronic obstructive pulmonary disease, type 2 diabetes mellitus, lower respiratory infections and lung cancers), infant mortality, adverse birth outcomes (low birthweight, small for gestational age and preterm births) and stunting cases. Health outcomes are further defined in Supplementation 2.

For consistency reasons, we used 2018 as the baseline year. The baseline health data was obtained through health reports published both locally and globally. For instance, baseline data related to children's health outcomes was collated from Indonesia Demographic and Health Survey, Indonesia Basic Health Survey (*Riset Kesehatan Dasar*), Indonesia Nutrition Status for Children Under 5 (*Status Gizi Balita*) and Indonesia National Report for Nutrition Status Monitoring (*Buku Saku Nasional Pemantauan Status Gizi*).

Health data projection

We used a national report to project the Indonesia population from 2018 to 2030 [25]. Both total and age-specific population were used to estimate the numbers of health outcomes included in the study. To estimate the numbers, we calculated the annual prevalence rates of each health outcome from historical data collected from the established health reports using simple linear regression. We assumed that the annual prevalence rates were constant throughout the year.

Estimation of health benefits

To estimate cause-specific deaths attributable to $PM_{2.5}$ pollution, we used methodology recommended by the Global Burden of Disease (GBD) Study 2019 [26]. A more detailed methodology to estimate the health benefits is described elsewhere [27]. Table 5 presents the relative risks (RR) used to estimate the health benefits from air pollution control strategies.

Table 5 Relative risks used to estimate health benefits from air pollution control strategies (for a 10 µg/m^3 change in $PM_{2.5}$ exposure)

Health endpoints	Age	RR (95% CI)	Reference
Children health outcomes			
Infant mortality, all-cause	1-12 months	1.09 (1.04, 1.14)	Heft-Neal et al. 2018 [28]
Stunting	< 5 years old	1.19 (1.10, 1.29)[a]	Pun et al. 2021 [29]
Adverse birth outcomes			
Low birth weight, at term	At birth	1.18 (1.06, 1.33)	Liu et al. 2019 [30]
Preterm birth	At birth	1.007 (1.005, 1.08)	Liu et al. 2019 [30]
Small for gestational age	At birth	1.08 (1.03, 1.13)	Pun et al. 2021 [29]

[a] RR estimate for household air pollution, with the assumption that underlies the impact of household air pollution is the same as the impact of ambient air pollution.

Except for total mortality attributable to $PM_{2.5}$, the RR estimates were applied to estimate cause-specific disease burdens attributable to air pollution using Eq. 2:

$$\Delta y = y_0[1 - e^{[-\beta(\Delta C)]}] \qquad \text{Eq. 2}$$

where:

Δy = Number of health outcomes attributable to risk factor

y_0 = Baseline number of health endpoints over the study period

β = Coefficient as the slope of the log-linear relationship between ambient air pollution concentrations and health outcomes, or the exponentiation of RR

ΔC = Difference in $PM_{2.5}$ concentration (BAU-RED) (in µg/m^3)

To compute the deaths averted if $PM_{2.5}$ concentration were to decrease, we used the following Eq. 3 and 4:

$$\Delta y^* = y_0 \times PAF_{\Delta c} \qquad \text{Eq. 3}$$

$$PAF_{\Delta c} = \frac{RR_{MR-BRT}(\Delta C) - 1}{RR_{MR-BRT}(\Delta C)} \qquad \text{Eq. 4}$$

where:

Δy^* = Averted mortality numbers

y_0 = Baseline number of mortality over the study period

$PAF_{\Delta c}$ = Proportional attributable fraction, which represents the fraction of mortality number attributable to $PM_{2.5}$ level change in RED and BAU scenario (ΔC)

$RR_{MR-BRT}(\Delta C)$ = Relative risk (from the MR-BRT model) attributable to $PM_{2.5}$ exposure at concentration ΔC (BAU-RED)

Assessment of Economic Benefits

This section shows the detailed methods to perform economic estimations. All the assumptions used are shown in Table 6.

Determining the unit cost per disease

We used the third wave of 2019 BPJS Kesehatan sample data that was published in 2021 which contains a sample of Indonesian National Health Insurance (INHI) participant data. The sample was randomly selected from the strata of INHI participants for the 2019 period. The data consists of, among others: i) membership, ii) visits of INHI participants who seek treatment at first-level health facilities (FKTP), iii) visits of INHI participants who seek treatment at Advanced Level Referral Health Facilities (FKRTL) and iv) treatment costs. We compared data between wave 2 (2018), wave 3 (2019) and wave 4 (2020) of the BPJS sample data. We found that the data in 2020 shows a completely different trend, most likely due to COVID-19, whereas 2019 data shows a relatively comparable trend with 2018. As such, we used 2019 data in our analysis to represent newer estimates. Using the data of INHI participants who seek treatment at FKRTL, we estimated that nationally there were 1,598,642 inpatient visits, or 138,405,670 patient visits after applying weights. The sample in DKI Jakarta Province in 2018 consisted of 46,850 outpatient and inpatient visits (or 7,227,665 visits after applying weights), and inpatient visits consisted of 3,948 visits (or 576,733 visits after applying weights).

Table 6. Assumptions used for economic impact estimates

No	Assumption	Amount
1	Exchange Rate USD 2019 (IDR)[1]	14,136

[1] https://www.exchangerates.org.uk/USD-IDR-spot-exchange-rates-history-2019.html

No	Assumption	Amount
2	Average Health Care Inflation (2014-2019)[2]	4.09%
3	**Mortality* & Infant death**	
	VSL US 2019 (USD)[3]	10,900,000
	PPP Indonesia to (USD)[4]	4,752
	VSL US 2019 (Rp)	51,796,800,000
	GNI Capita Indo Current (Rp)[5]	56,944,774
	GNI Capita USA Current (USD)[6]	66,289
	GNI Capita USA Current (Rp)	315,005,328
	Elasticity	1.5
	VSL Indonesia 2019 (GNI Capita USA - Indo PPP) (Rp)	3,981,134,876
	VSL Indonesia 2019 (GNI Capita USA - Indo PPP) (USD)	837,781
4	**Stunting**	
	Cost of Stunting Prevention 2013 (USD)[7]	102.99
	Cost of Stunting Prevention 2019 (USD) adjusted by health care inflation	128.26
	Cost of Stunting Prevention 2019 (IDR) adjusted by health care inflation	1,813,189.34
5	**Preterm births**	
	Direct Cost	
	Cost/Case (2019) (USD)[8]	675
	Indirect Cost	
	Minimum Wage Jakarta (2019)/months (USD)	279
	Day work/month	20
	Minimum Wage Jakarta (2019)/day (USD)[9]	14
	Parent stay (person)	2
	Hospitalization stays (days)[10]	23
	Indirect Cost/case (2019) (USD)	633.49
	Total Cost (direct+indirect) (USD)	1,308.91
6	**Low Birth**	
	Direct Cost	
	Cost/Case (2019) (USD)[11]	828
	Indirect Cost	

[2] https://www.statista.com/statistics/1005580/indonesia-annual-inflation-rate-of-healthcare/
[3] https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-on-valuation-of-a-statistical-life-in-economic-analysis
[4] https://data.worldbank.org/indicator/PA.NUS.PPP?locations=ID
[5] https://data.worldbank.org/indicator/NY.GNP.PCAP.CN?locations=ID
[6] https://data.worldbank.org/indicator/NY.GNP.PCAP.CN?locations=US
[7] https://onlinelibrary.wiley.com/doi/10.1111/mcn.12080
[8] BPJS 2019 Sample
[9] https://invest.jakarta.go.id/labor
[10] BPJS 2019 Sample
[11] BPJS 2019 Sample

No	Assumption	Amount
	Minimum Wage Jakarta (2019)/months (USD)	279
	Day work/month	20
	Minimum Wage Jakarta (2019)/day (USD)[12]	14
	Parent stay (person)	2
	Hospitalization stay (days)[13]	6
	Indirect Cost/case (2019) (USD)	159.86
	Total Cost (direct+indirect) (USD)	987.54
7	**Small for gestational age**	
	*Total Cost (direct+indirect) (USD)**	1,308.91

*Total cost for small gestational age is assumed to be the same with preterm birth due to lack of data

Estimating hospitalization days

The average inpatient length of stay was calculated from the sample data of INHI participants who sought treatment at FKRTL. We estimated the average length of inpatient days in 2019 for each of the diseases following the same ICD-10 codes used in estimating health impact in DKI Jakarta Province.

Estimating inpatient health care cost

We estimated the inpatient treatment cost per disease using the costs available in 2019 BPJS sample data. We divided the total treatment cost per year of each disease by its respective number of visits from the same data to estimate the unit cost of treatment per case. The types of diseases are similar to the types of diseases estimated in the health impact calculation (using the same ICD-10 codes). We multiplied the unit cost by the number of attributable cases per diseases to obtain the total treatment cost due to air pollution. We adjusted the nominal value of treatment cost using the Indonesian health care cost inflation rate [31].

Non-health care cost

We assumed that patients who undergo inpatient care will lose productivity during their stay, resulting in a non-health care cost. We used the monthly minimum wage of

[12] https://invest.jakarta.go.id/labor
[13] BPJS 2019 Sample

Jakarta Province as a proxy of productivity value. We divided this monthly value by twenty days to obtain daily productivity loss. We multiplied daily productivity loss by the average inpatient days for each case per disease to obtain productivity loss per case.

Estimating the value of statistical life year (VSL)

Our estimation of Indonesian VSL is based on the approach developed by Robinson et al [32], using Eq. 5:

$$VSL_{Target} = VSL_{US} \times (\frac{GNI_{Target}}{GNI_{US}})^{elasticity} \quad \text{Eq. 5}$$

Subsequently, we used the elasticity of 1.5, following the same study by Robinson et al. to make it consistent [32]. We found the 2019 VSL in Indonesia to be US$837,781. We multiplied the number of attributable deaths due to pollution by the amount of VSL to determine the value of loss due to deaths.

Estimating the cost of stunting

The cost of treating stunting was proxied by the cost of interventions to prevent stunting. This followed the study by Hoddinott et al. [33], where the cost of preventing stunting is considered as the value that we gain by preventing stunting. We adjusted the cost of preventing stunting in 2013 into 2019 value using Indonesia health care inflation estimate [31].

RESULTS

Modeling of Air Quality Impacts of Emission Scenarios

Emissions projections under BAU scenario

Trends of $PM_{2.5}$, NOx and SO_2 emissions under a BAU scenario are presented in Figure 3. Note that the scenario has also considered the mobilization of civil servants from Jakarta to the new capital city in Kalimantan Island (IKN scenario). This assumed movement of 1.5 million people by 2024 will also affect transportation and residential emissions. Emissions of $PM_{2.5}$, NOx and SO_2 increased over the time period of 2018-2030 but slight reduction was seen in 2020 due to the COVID-19 pandemic. The increasing rate for each air pollutant was largely driven by the increasing rate of activity data in on-road mobile sources, except for SO_2, which was mainly contributed by the industrial emission source. Under the BAU-IKN scenario, emissions increased slightly less due to the impact on activity data reduction in transportation and residential sectors.

Figure 3. Projected $PM_{2.5}$, NOx, and SO_2 emissions under BAU scenario

Emissions reductions

The results for $PM_{2.5}$, NOx and SO_2 emission reductions are presented in Table 7. The highest range of $PM_{2.5}$ emission reduction in 2030 was seen for OTR4 of 1,245-1,316, followed by OTR5 of 952–1,000 ton/year, for 2025 and 2030, respectively. OTR4 emphasized an ambitious target of emission testing to be done for all PCs, to be followed up by maintenance to comply with Euro 4. This resulted in significant emission reduction of $PM_{2.5}$ emissions as well as NOx and SO_2 emissions. This has to be accompanied by fuel-quality improvement to reduce sulfur content to below 50 ppm. OTR5 focused on collective shifting to public transportation systems (i.e., MRT, LRT, busway) by 60% in 2030, which could help to slow down the use of private vehicles, therefore reducing the MC and PC vehicle kilometers traveled.

Table 7 Emission reductions of all measures for $PM_{2.5}$, NOx and SO_2 (in tons/year)

Code	Measures	$PM_{2.5}$		NOx		SO_2	
		2025	**2030**	**2025**	**2030**	**2025**	**2030**
OTR1	Governmental operational electric vehicle (all fleet)	105	111	207	218	54	58
OTR2	Stringent emission standard for microbus to comply Euro 4	460	486	7,890	8,305	141	152
OTR3	Transjakarta electric buses (annual addition of unit)	272	288	670	705	111	119
OTR4	Regular emission testing (target to comply at least Euro 2)	1,245	1,316	5,726	6,027	226	243
OTR5	Shifting to public transportation	952	1,006	20,614	21,699	40	43
RES	Conversion from LPG stove to electric stove	4	4	578	608	6	6
DUST	Dust control from construction activity	665	702	NA			
OB	Ban of municipal solid waste open burning	231	244	86	91	14	15
Total emission reduction for collective implementation (ton/year)		3,935	4,157	35,770	37,653	592	637

Note: NA = not applicable, as this measure targets only PM emission reduction

Meteorological modeling

Meteorological parameters required by AERMET consisted of two groups: i) surface meteorological parameters (i.e., wind speed and direction, temperature, relative humidity, cloud cover) taken from the standard meteorological station located at Halim Perdanakusuma Airport, and ii) upper-air parameters taken from Soekarno Hatta Airport (wind speed and direction, pressure, dew temperature, relative humidity) for the year of 2019. Note that upper-air data was not measured at Halim Perdanakusuma airport; those available at the Soekarno Hatta airport were taken instead. Surface meteorological conditions were not taken from the Soekarno Hatta airport due to its proximity to coastal areas, therefore such data were taken from Halim Perdanakusuma. The wind rose for the year 2019 is presented in Figure 4.

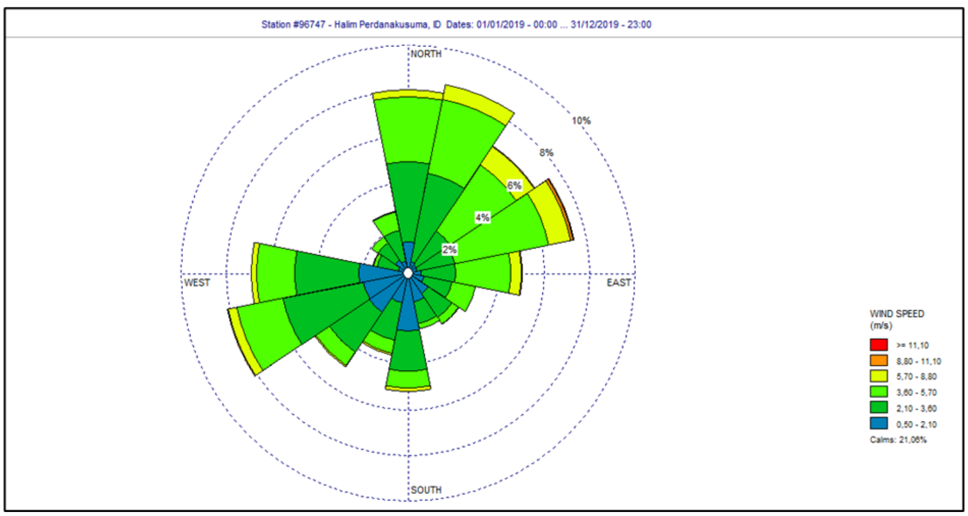


Figure 4: Wind rose at Halim Perdanakusuma airport for the year of 2019. Throughout the year, northeasterly (NE) wind dominates the wind direction, followed by the southwesterly (SW) wind direction. This reflects the effects of synoptic winds following the monsoon circulations. Northeasterly wind was characterized by moderate wind speed of 3-5.7 m/s, while SW wind had lower wind speed compared to NE.

Spatial distribution of emissions

Spatial distribution of relevant measures of emissions for line sources are presented in Figure 5, while area sources are presented in Figure 6. Emission densities were higher in OTR5 and OTR4 and well-allocated along the major road networks in Jakarta. Fewer emission reductions were seen for OTR1 and OTR3, as they had the lowest emission reduction compared to others. As seen in Figure 6, the highest density of emission reduction is for DUST, which emphasized measure implementation to control particulate matter emission from construction activities. This was followed by the OB scenario to ban municipal solid waste open burning in Jakarta, which shows higher emission density over especially dense population areas. Note: Emission reduction densities are shown in different color scales.

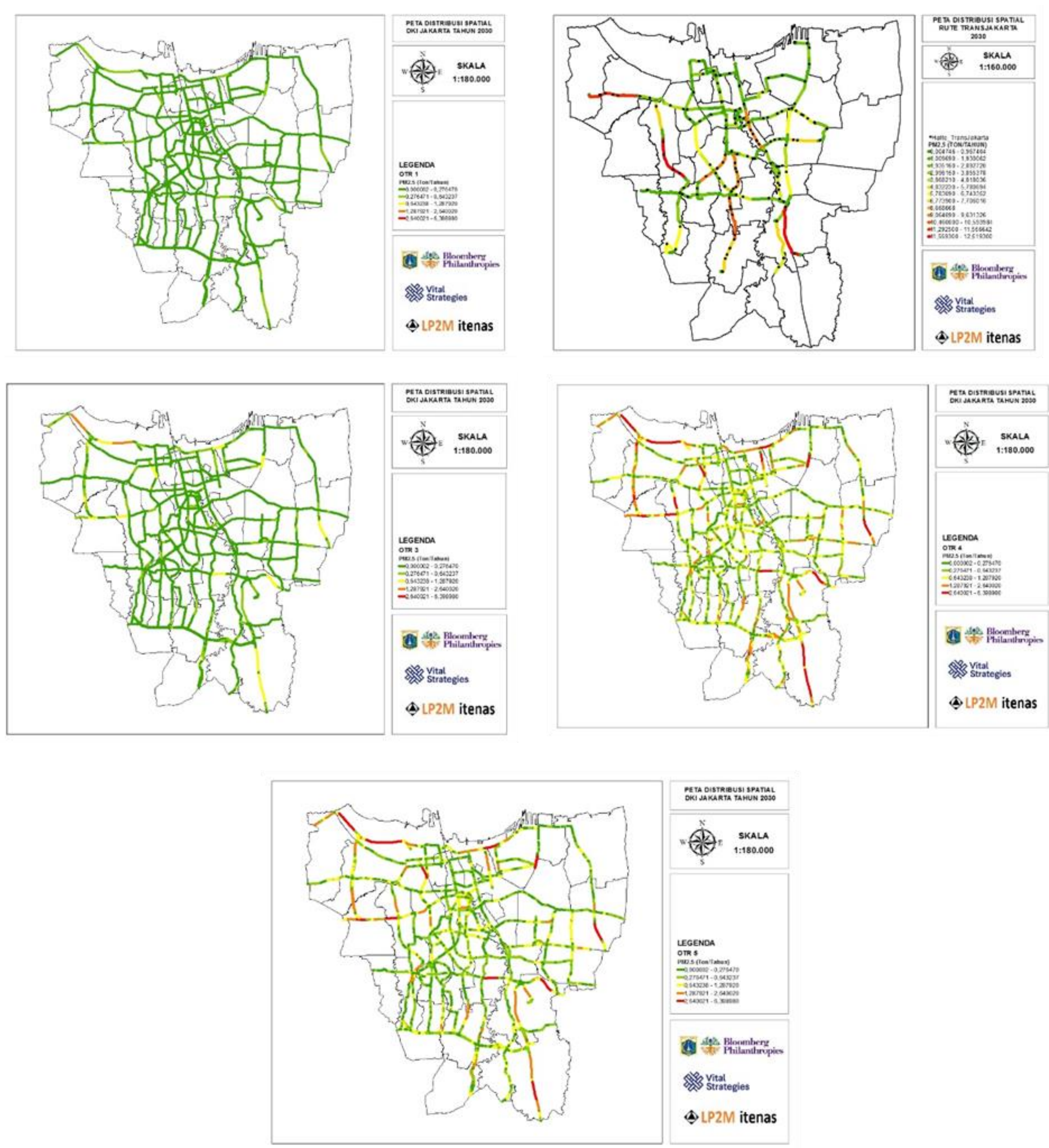


Figure 5. Spatial distribution of emission reduction for on-road transport relevant measures.

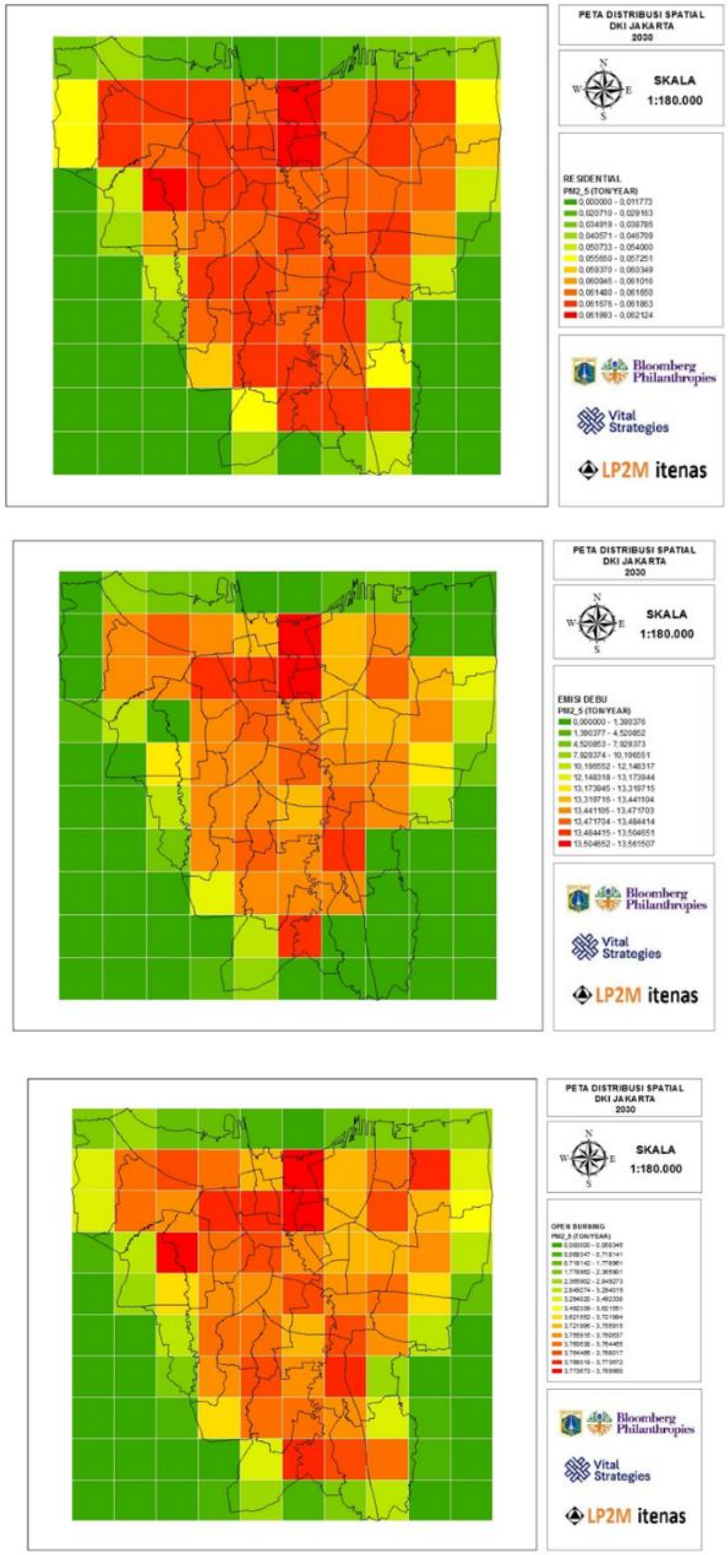


Figure 6. Spatial distributions of emission reduction for area sources

$PM_{2.5}$ air quality impacts

Results for $PM_{2.5}$ annual average concentrations for the year 2030 are presented in Figure 7, while those for the year 2025 are presented in Supplementation 3. In addition, impacts of emission reduction scenarios on $PM_{2.5}$ air quality are important to quantify health benefits, therefore the results for all scenarios (grouped into on-road mobile and area sources) are highlighted in this section.

We extracted both domain maximum annual average and domain average values of $PM_{2.5}$ concentrations for all measures presented in Figures 7 and 8. Emission reductions achieved under the OTR4 scenario resulted in the highest domain average $PM_{2.5}$ concentration reduction of 1.5 μg/m^3 as compared to others. The domain maximum $PM_{2.5}$ concentration reduction was 5.7 μg/m^3. Note that this was more than the latest WHO guideline value for the annual average of 5 μg/m^3. The distribution pattern of $PM_{2.5}$ concentration reductions was seen in several road networks where the emission reductions were also high, owing to the significant impacts of primary $PM_{2.5}$ emission reduction. In terms of the magnitude of the $PM_{2.5}$ concentration reduction, OTR5 contributed the second following the OTR4. The emission reductions of $PM_{2.5}$ resulted from the public shifting from private vehicles to public transportation in Jakarta, resulting in the maximum $PM_{2.5}$ concentration improvement of 4.5 μg/m^3 in 2030. The average concentration reduction under this scenario in the domain was the lower 1.1 μg/m^3, as seen in Figure 7. The lowest impact was seen for the OTR1, with a domain average $PM_{2.5}$ concentration reduction of 0.13 μg/m^3 and a domain maximum concentration of 0.48 μg/m^3. For OTR2 and OTR3, the domain average $PM_{2.5}$ concentration reductions were 0.56 and 0.32 μg/m^3, respectively. The domain maximum concentrations were simulated at 2.1 and 1.2 μg/m^3, respectively. Higher values were seen consistently in areas close to active road networks in the city with high traffic volume and congestion.

For area sources presented in Figure 8, the highest magnitude of $PM_{2.5}$ concentration reduction was achieved by the DUST scenario, followed by OB and RES. Dust control from construction activities (DUST) yielded the domain average $PM_{2.5}$ concentration reduction of 0.71 μg/m^3, while the annual average domain maximum concentration was 2.4 μg/m^3. Significant contribution was given by the OB scenario of 0.7 μg/m^3 and 0.24 μg/m^3 for domain maximum and domain average concentrations, respectively. The contribution of the RES scenario was negligible, only 0.1 μg/m^3 for domain maximum concentration and far lower than that for the domain average concentration.

Note that this simulation allows only the impact of primary emissions of $PM_{2.5}$ and neglects the secondary aerosol formation, which also contributes to $PM_{2.5}$ levels in the study area. Interaction with photochemical smog pollution was not possible, as it is only able to be done using a one-atmosphere model.

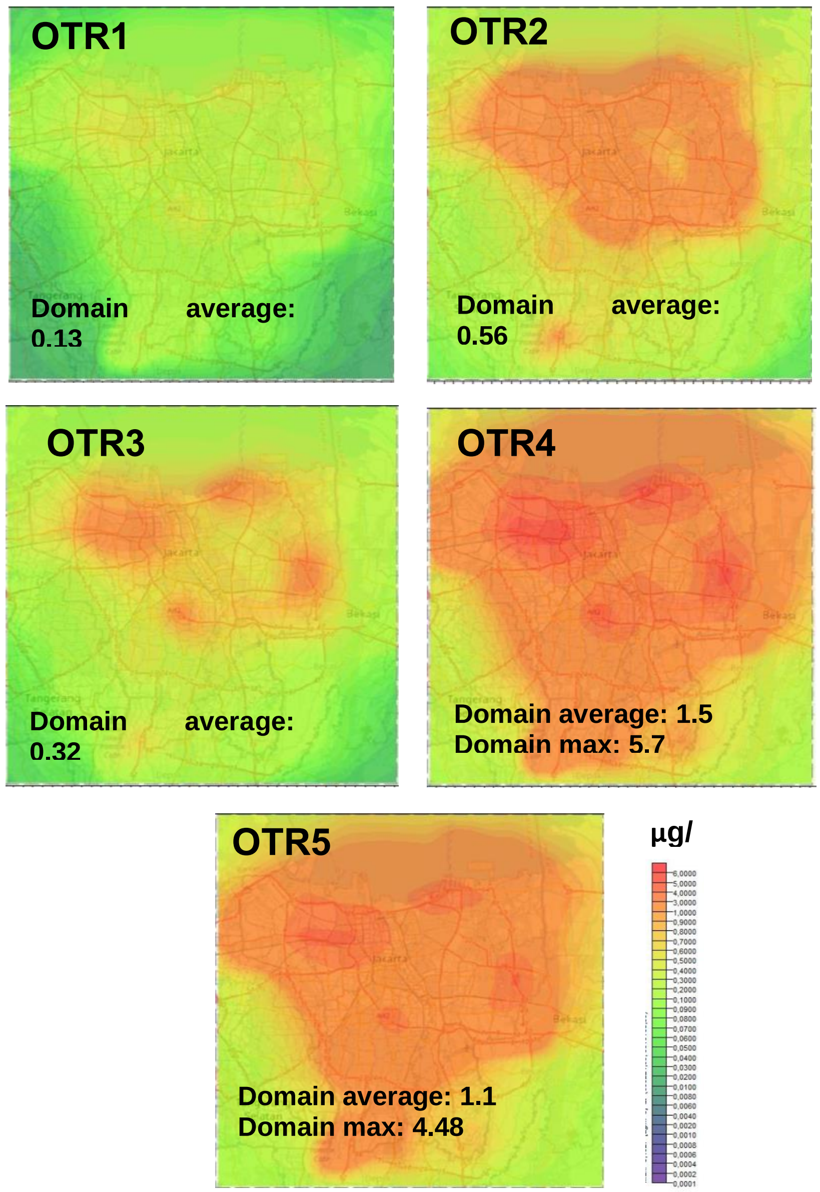


Figure 7. Annual average of $PM_{2.5}$ for the year 2030 for on-road mobile source relevant measures. Note: domain average and domain max. concentrations are presented in µg/m³.

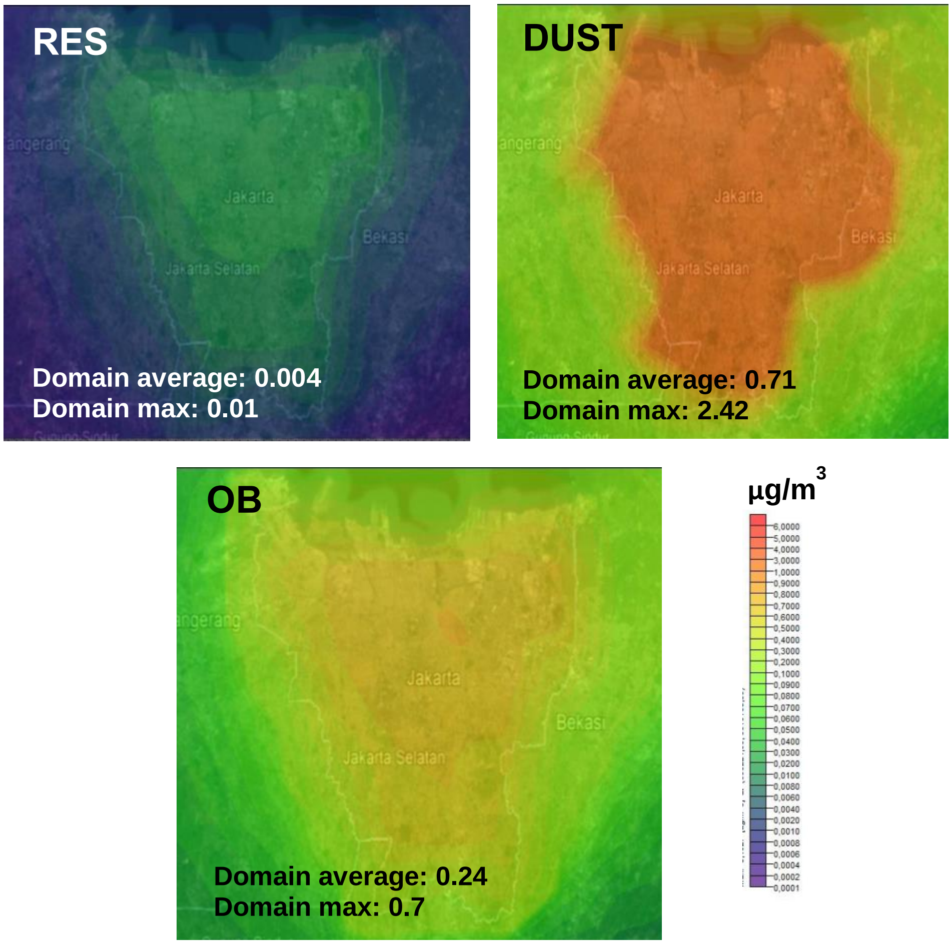


Figure 8. Annual average of $PM_{2.5}$ for the year of 2030 for relevant area sources: RES, DUST & OB. Note: domain average and domain max. concentrations are presented in μg/m^3.

Modeling summary

This part summarizes the efficacy of all measures in terms of emission and concentration reductions. Figure 10 describes the relation between $PM_{2.5}$ emission reductions for all measures and the associated concentration reductions. According to the modeling results, OTR4 has the highest efficacy, followed by the OTR5 and DUST scenarios. RES has the lowest efficacy, followed by the OTR1 and OB scenarios. OTR2 and OTR3 have moderate efficacy. Collective implementation of all scenarios would help to maximize the $PM_{2.5}$ air quality improvement in Jakarta.

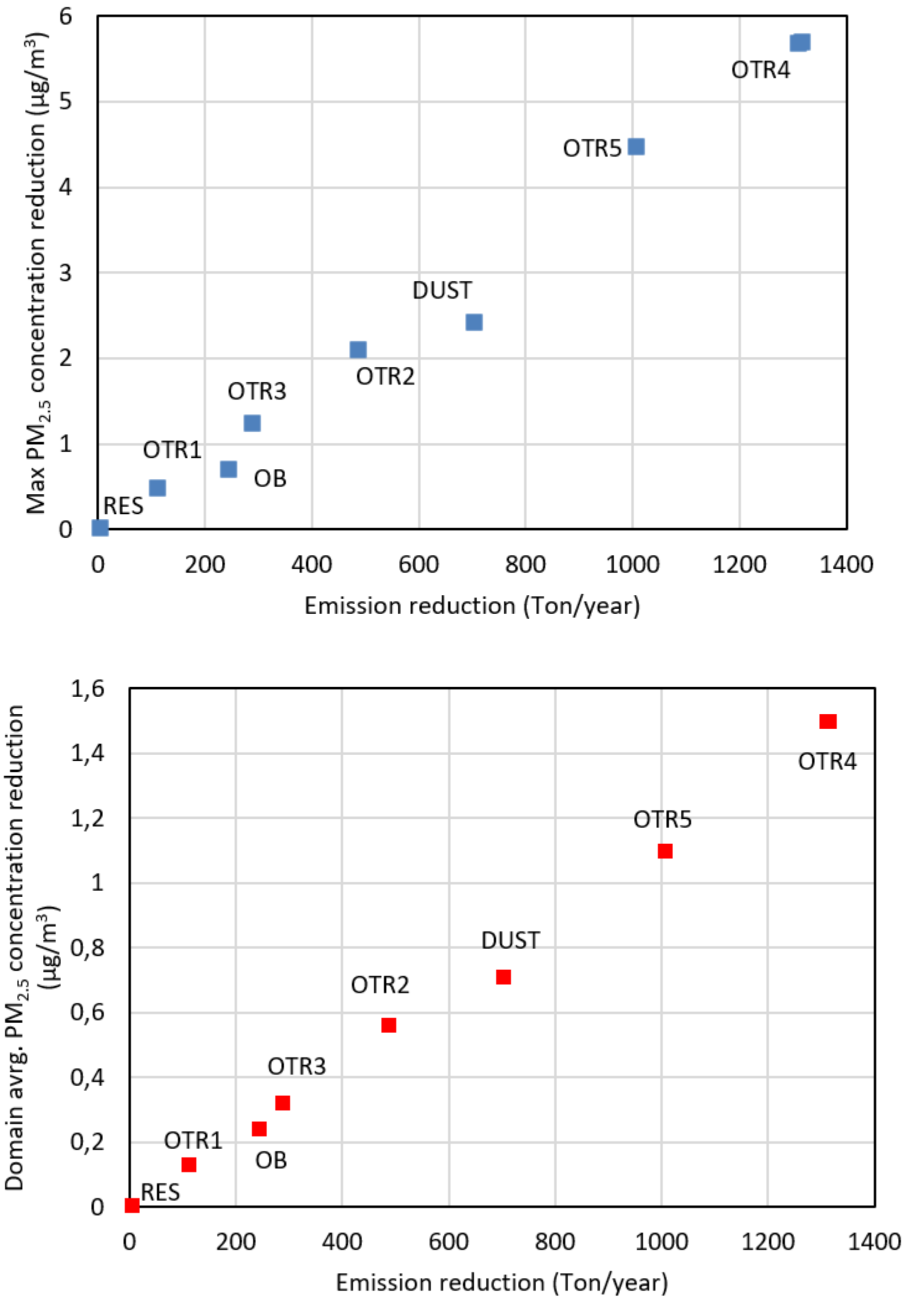


Figure 9. Summary of efficacies of all measures

Cost for Implementing Air Pollution Control Strategies in Jakarta

OTR1: Government operational electric vehicles program

Motorcycles have the highest annual growth rate, 4.7%, followed by passenger cars at 3.6% and cargo cars at 2.9%. As predicted, the number of buses increases at the lowest rate of 0.3% per year. The number of government-KDOs in DKI Jakarta in 2015 was 322 units [34]. By observing the data provided by the BPS, the growth of government-KDOs in DKI Jakarta must be lower than 4.4% annually. Therefore, we assume that the annual growth for government-KDOs will be 1% for motorcycles and 0.5% for cars [35]. Using the number of government-KDOs in 2015 and their annual growth, we project the number of government-KDOs in DKI Jakarta using a linear trend as shown in Figure 10.

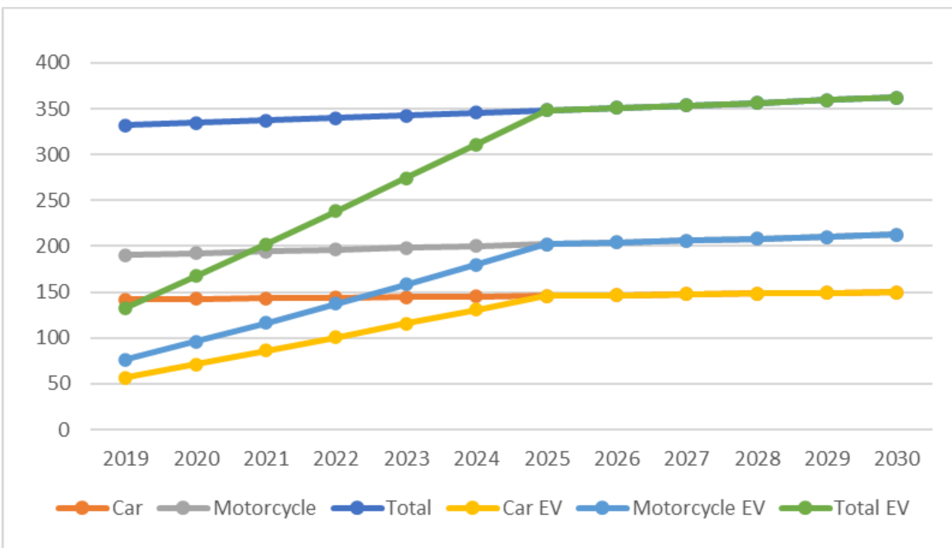


Figure 10. Projection of number of government-KDOs and EV in DKI Jakarta 2019-2030 (in unit).

According to Figure 10, the number of government-KDOs in DKI Jakarta was projected to reach 340 units by 2022, comprising 143 cars and 196 motorcycles. By 2030, this number is expected to rise to 362 units. By 2022, we estimated number of government-KDO EVs to reach 238 units, consisting of 101 EV cars and 137 EV motorcycles. By 2030, the number of KDO EVs is expected to reach 362 units.

Figure 11 shows the estimation of the annual cost to procure government-KDO EVs using the annual target of the projected number of government-KDOs. According to the figure, the total annual cost was estimated to be IDR18.09 billion by 2022. Meanwhile, the total annual cost will decrease to IDR0.9 billion by 2030. The higher cost in the initial year is due to the high percentage target, as shown in Table 4. In the following years, the incremental cost increases slowly.

Figure 11. Annual costs for Government EV program in DKI Jakarta 2019-2030 (in billion IDR).

OTR2: Stringent emission standard for microbus to comply with Euro 4

Projected numbers of public transport in 2022-2030 are illustrated in Figure 12. The number of public transport units in 2022 is estimated to be 27,600, declining to 21,400 units in 2025. Following the annual target (as shown in Table 4), we estimate that only 5,500 units (20%) of public transport will meet the emission standards by 2022. In 2025, all public transport will meet the emission standards.

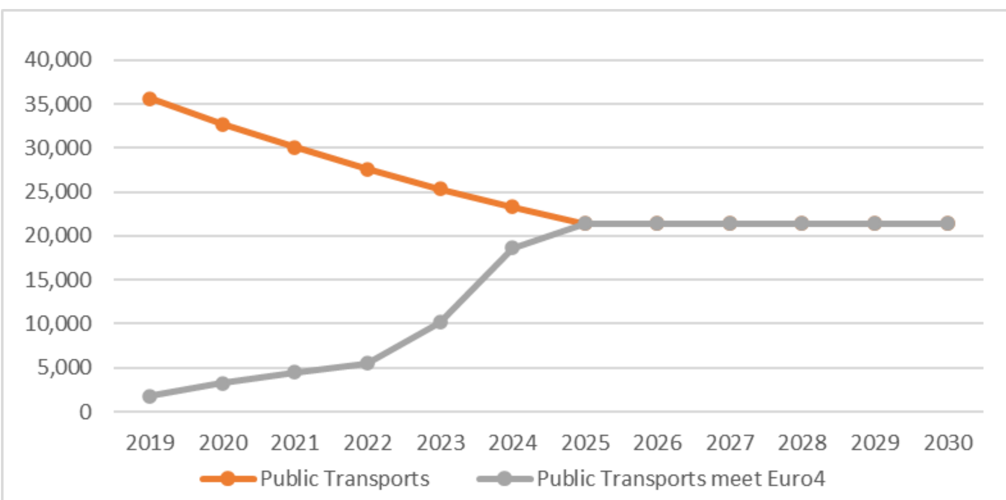


Figure 12. Number of public transports in DKI Jakarta 2019-2030 (in thousands of units).

By 2022, the projected number of public transport that meets Euro 4 standards is 5,500 units (Figure 12). With this number, the total subsidies needed to meet the demand is IDR212 billion (for diesel, the subsidy is IDR10,300/liter and an annual diesel consumption of 3,700 liters/year). In the same way, the total subsidies needed up to 2030 will be around IDR7.4 trillion, as shown in Figure 13. The cost of subsidies will increase from 2022 and peak in 2025, when all public transport meets the Euro 4 standards.

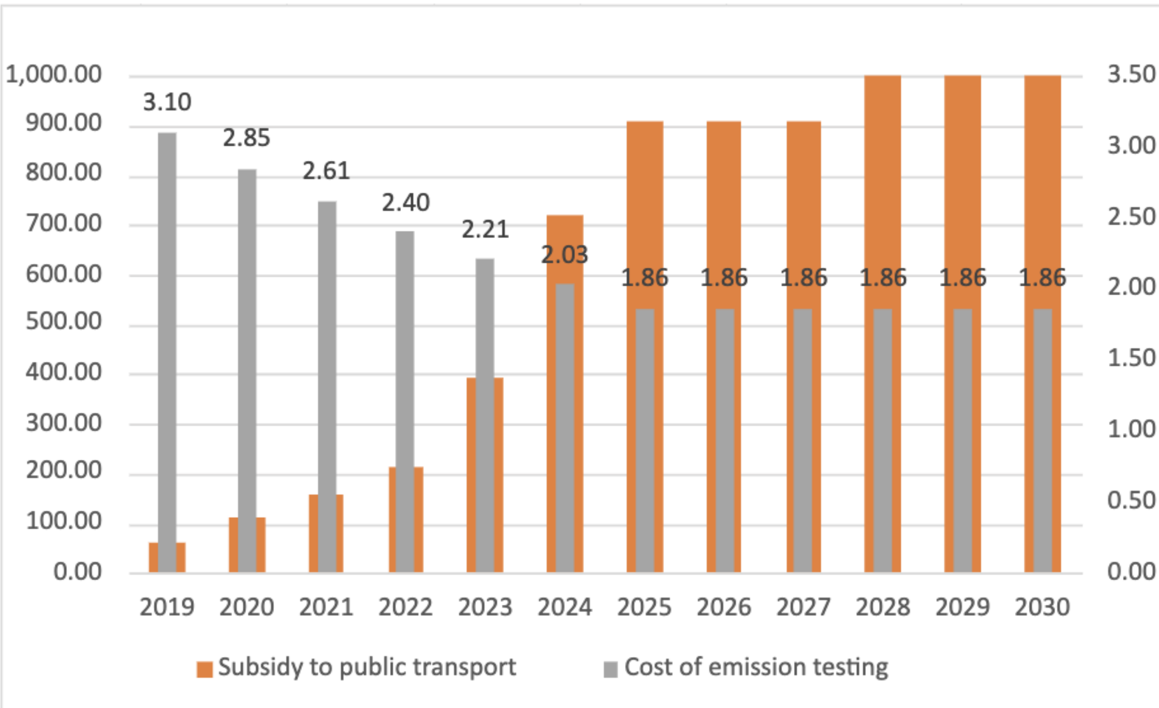


Figure 13. Annual costs for emission standard program for public transportation in DKI Jakarta 2019-2030 (in billion IDR). The right y-axis represents the cost of emission testing, the left y-axis shows subsidy of public transport.

Apart from the process of switching fuel sources to Dexlite CN51, the program for implementing Euro 4 standards for public transport is also carried out through the KIR test, a series of vehicle tests to verify that the vehicle is technically fit for use on the highway. Emissions testing is required in the assessments. The KIR test is mandatory for all passenger and cargo vehicles. For minibuses, the KIR test fee in DKI Jakarta is about IDR87,000 [36]. When all public transport is assumed to take the mandatory KIR test, the total cost required for KIR testing in the 2022-2030 period is IDR17.8 billion.

OTR3: Transjakarta electric buses

As shown in Figure 14, the cost of annual procurement of electric buses is estimated to be IDR200 billion each year. We expect increasing annual maintenance costs due to the growing number of electric buses every year. The total cost will reach IDR220 billion by 2019 and increase to IDR380 billion by 2030. The total implementation cost for this program is IDR3.57 trillion.

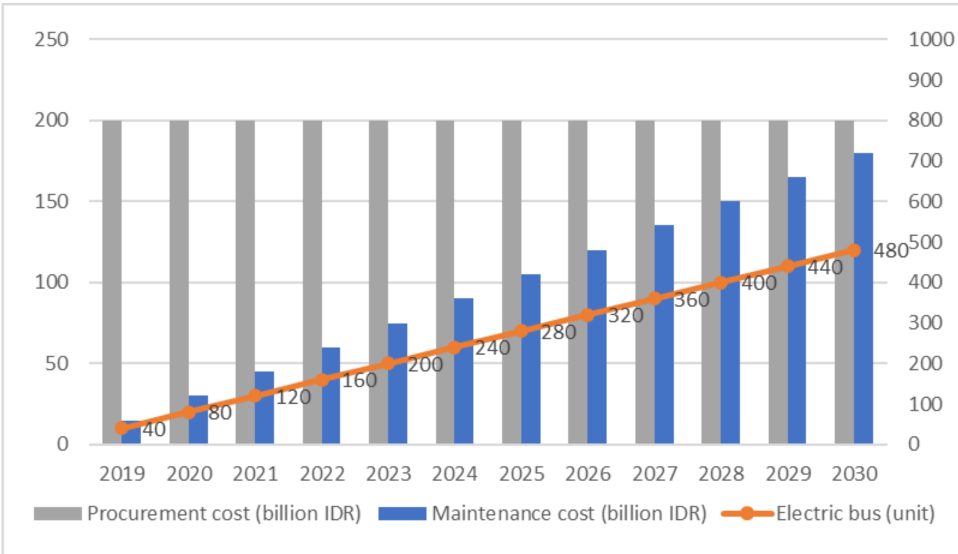


Figure 14. Number of electric Transjakarta buses (in units) and their annual costs in DKI Jakarta 2019-2030 (in billion IDR). The left y-axis represents procurement and maintenance costs, the right y-axis is the number of electric buses.

OTR4: Emission test program for private vehicles

Figure 15 shows the projected number of private vehicles in Jakarta from 2019-2030. By 2022, the total number of private vehicles will reach 21.4 million units, consisting of 17.2 motorcycles and 4.2 cars. By 2030, the total number of private vehicles will reach 28.9 million units. Using the targets set for this program, we can identify the number of vehicles that have taken an emissions test. By 2022, vehicles with emission tests might reach 4.28 million units, consisting of 3.44 million motorcycles and 0.84 million cars. By 2030, vehicles with an emission test may reach 28.90 million units.

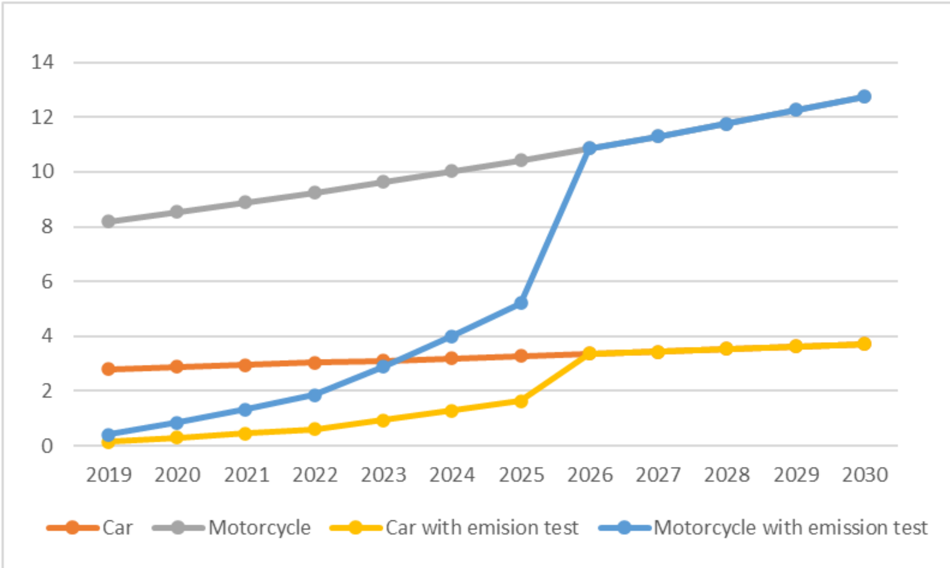


Figure 15. Number of private vehicles in DKI Jakarta 2019-2030 (in million units).

As shown in Figure 16, by 2022, the cost of implementing this program may reach IDR529 billion, and it will increase to IDR3.5 trillion by 2030. This high increase starts in 2026, when we project that 100% private vehicles have taken the emission test.

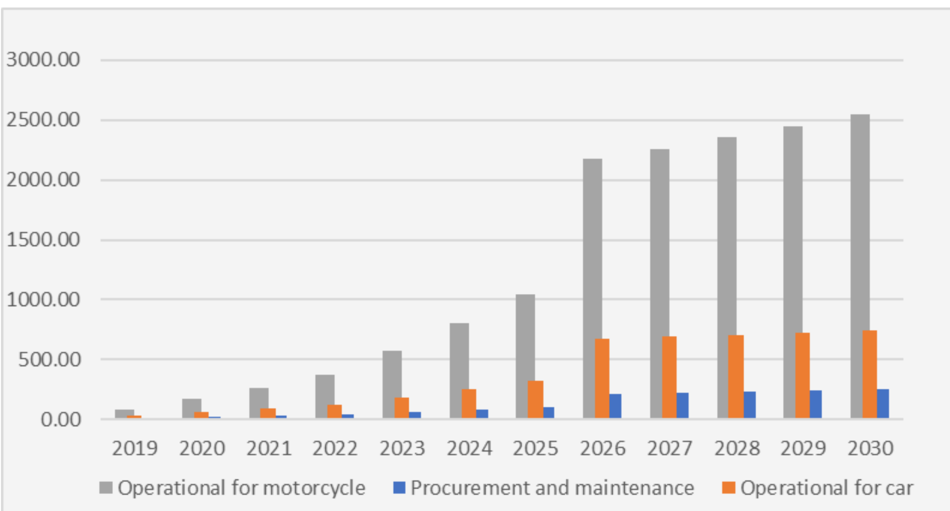


Figure 16. Annual costs for emission testing program for private vehicle in DKI Jakarta 2019-2030 (in billion IDR).

OTR5: Shifting to public transport

Figure 17 shows annual target for public transport shifting percentage, projected number of private vehicles, and number of passengers in private vehicles from 2019-2030. By 2022, 19.8% of private passengers will shift to public transport. It continues to increase gradually each year, reaching 30% by 2025 and 60% by 2030.

The number of passengers in private vehicles by 2022 is estimated at 25.6 million and will increase to 34 million by 2030. By 2022, 19.8% of total passengers, or 5.06 million people, would shift to public transport. This number continues to increase and will reach 20.4 million people by 2030.

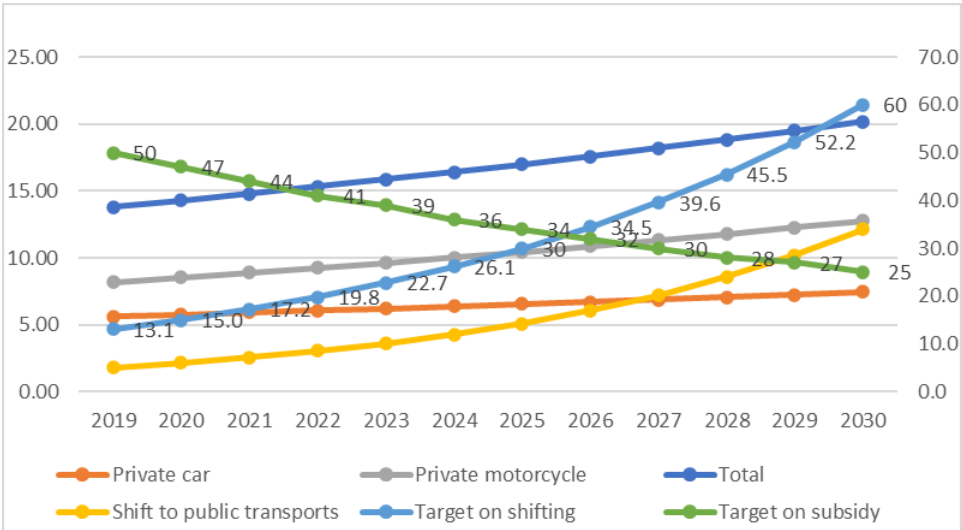


Figure 17. Target private passenger shifting and target for subsidy (%) and number of private passenger and passenger shifting in DKI Jakarta 2019-2030 (in million people). The left y-axis for number of private vehicles and number of passengers shifting the right y-axis for target on shifting and subsidy.

The projected numbers of Jabodetabek train passengers are 413 million by 2022 and 444 million by 2030 (Figure 18). The projected annual cost of KRL per passenger is IDR7,900 by 2022 and will increase to IDR24,100 by 2030. Combining all the information, the total operating cost is estimated to reach IDR40.4 billion by 2022 and IDR493 billion by 2030.

Increasing operational costs due to the increasing number of passengers also occurred in Transjakarta buses. The number of Transjakarta passengers is projected to reach 460 million by 2022and increase to 552 million by 2030. Based on Transjakarta’s reported revenue in 2020 and 2021, they had annual revenue growth of 28.66%. Thus, the projected Transjakarta annual cost per passenger is IDR2,500 by 2022 and will increase to IDR15,600 by 2030. Total additional operational costs in 2022 will reach IDR12.6 billion by 2022and increase to IDR319 billion by 2030.

According to the above information, the annual subsidy cost needed will reach IDR6 trillion by 2022 and IDR12 trillion by 2030. Therefore, the total annual subsidy for the entire period of 2022-2030 will reach 79 trillion IDR.

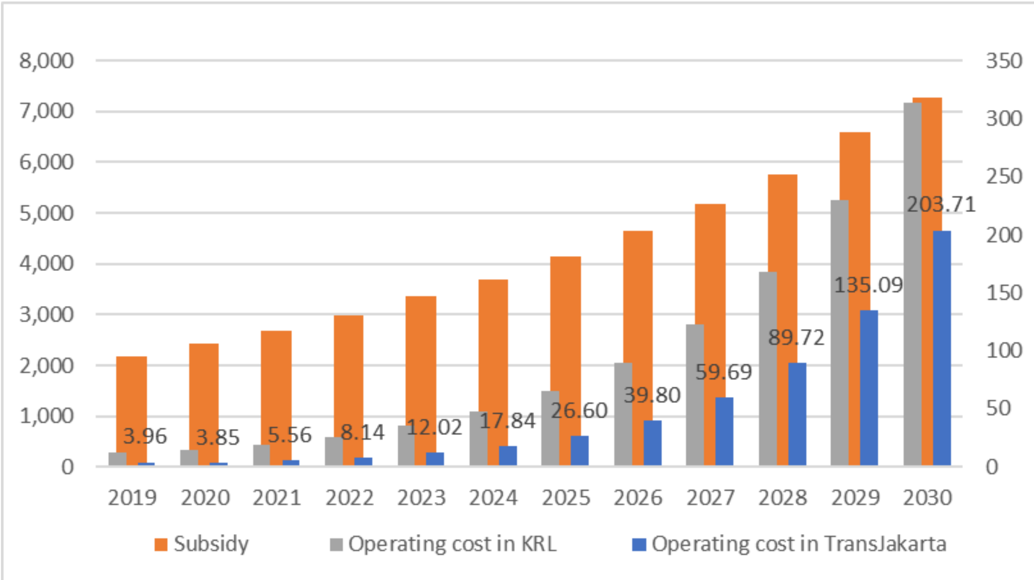


Figure 18. Annual costs for shifting program to public transport in DKI Jakarta 2019-2030 (in billion IDR). The left y-axis shows subsidy, the right y-axis is operating cost.

RES: Conversion from LPG stove to electric stove

The number of households is projected to reach 3.2 million by 2022 and will increase to 10 million by 2030 (Figure 19). The costs required for this conversion program will reach IDR87 billion by 2020 and increase to IDR2.5 trillion by 2030. Thus, the estimated total cost in the 2022-2030 period is IDR7.2 trillion.

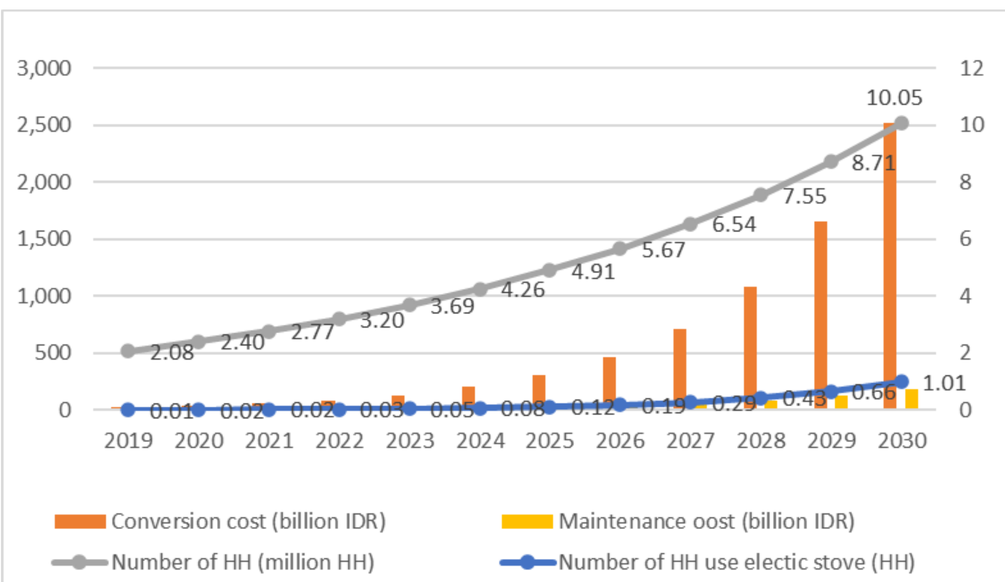


Figure 19. Number of households that use electric stoves (in number of HH) and the annual cost of program conversion and maintenance in DKI Jakarta 2019-2030 (in billion IDR). The left y-axis shows conversion and maintenance cost, the right y-axis is the number of HH and HH with electric stoves.

DUST: Dust control from construction activity

The projected monitoring cost will reach IDR289 million by 2023 and IDR413 million by 2030, as shown in Figure 20. Thus, the total cost of monitoring emission standards in the form of environmental monitoring programs will reach IDR2.9 billion for the entire 2022-2030 period.

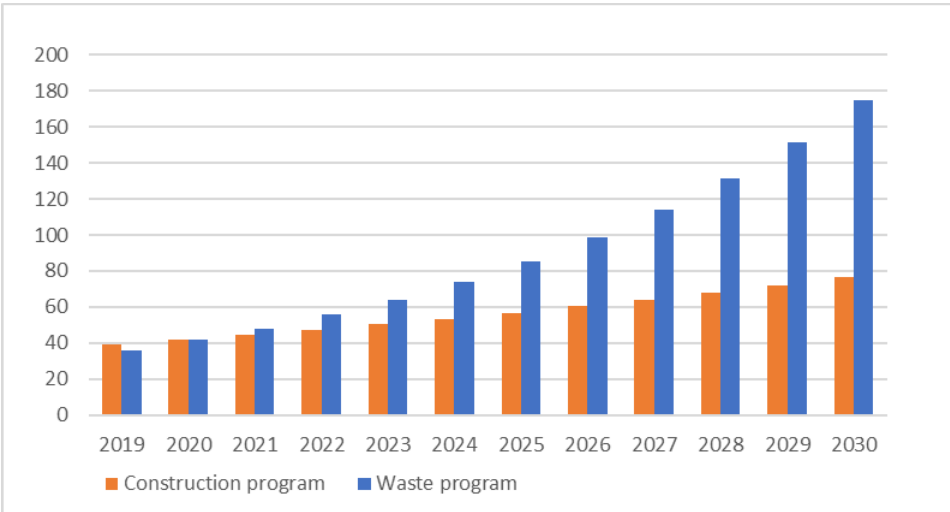


Figure 20. Annual cost of monitoring emission standard for construction activity and household waste in DKI Jakarta 2019-2030 (in billion IDR).

OB: Ban of municipal solid waste open burning

The total costs required will reach IDR723 million by 2024 and increase to IDR1.7 billion by 2030, as shown in Figure 20. Thus, the total cost of monitoring household waste and prohibiting open burning will reach IDR8.1 billion by 2022-2030.

Total cost of programs

The total costs required to implement these eight strategic programs are shown in Table 8. Using the 2019 base year, the total costs will reach IDR3.93 trillion by 2022 and increase to IDR14.54 trillion by 2030. Cumulatively, the total cost required by 2022-2030 will reach IDR87.83 trillion in the 2019 base year. Furthermore, when compared with intervention programs, the results are shown in the last column. The strategic program with the highest cost is shifting to public transport. That is followed by the programs with the second and third highest cost, emission tests program for private vehicles and shifting household energy. The strategic programs with the lowest cost are the government EV program and emission standards for construction activity.

Table 8. Annual cost for each program intervention for air quality improvement in DKI Jakarta 2019-2030 (in IDR and USD).

Program	**2019 (in trillion IDR)**	**2020 (in trillion IDR)**	**2021 (in trillion IDR)**	**2022 (in trillion IDR)**	**2023 (in trillion IDR)**	**2024 (in trillion IDR)**	**2025 (in trillion IDR)**	**2026 (in trillion IDR)**	**2027 (in trillion IDR)**	**2028 (in trillion IDR)**	**2029 (in trillion IDR)**	**2030 (in trillion IDR)**	**Total (in trillion IDR)**	**Total (in million USD)**
Government Electric Vehicle (EV)	0.071	0.020	0.021	0.021	0.021	0.022	0.022	0.004	0.004	0.005	0.005	0.005	0.221	15.90
Emission standard for public transportation	0.065	0.116	0.159	0.215	0.393	0.720	0.909	0.909	0.909	1.000	1.000	1.000	7.396	532.02
Public electric buses	0.215	0.230	0.245	0.260	0.275	0.290	0.305	0.320	0.335	0.350	0.365	0.380	3.570	256.82
Emission test for private vehicles	0.119	0.245	0.382	0.529	0.821	1.136	1.474	3.057	3.171	3.291	3.414	3.542	21.182	1,523.77
Shifting to public transportation	2.179	2.436	2.715	3.015	3.419	3.766	4.248	4.780	5.367	6.013	6.965	7.787	52.690	3,790.40
Shifting household energy	0.027	0.041	0.062	0.094	0.143	0.217	0.331	0.504	0.766	1.166	1.775	2.701	7.826	562.96
Emission standard for construction activity	0.039	0.042	0.045	0.047	0.050	0.053	0.057	0.060	0.064	0.068	0.072	0.077	0.675	48.56
Controlling household waste	0.036	0.042	0.048	0.056	0.064	0.074	0.085	0.099	0.114	0.131	0.151	0.175	1.075	77.31
Total	2.752	3.172	3.676	4.237	5.187	6.279	7.431	9.733	10.731	12.024	13.747	15.666	94.634	6,807.73
Total adjusted for inflation rate in 2019	2.554	2.944	3.412	3.933	4.814	5.828	6.897	9.033	9.960	11.160	12.759	14.540	87.835	6,318.60

Health impact benefits

We find that, in total, more than 32,000 cause-specific deaths, almost 300 infant deaths, more than 12,000 stunting cases and more than 2,000 adverse birth conditions can be averted if the listed strategies to control air pollution can be implemented in Jakarta by 2030. Table 9 describes more detailed health benefits obtained from each strategy.

Table 9. Total number of health benefits obtained by each air pollution control strategy in Jakarta (in cases)

	OTR1	OTR2	OTR3	OTR4	OTR5	RES	DUST	OB	Total
Cause-specific mortality*	910	3,925	2,320	10,131	8,093	0	4,945	1,740	32,064
Infant mortality	8	35	21	95	73	0	44	15	292
Stunting	349	1,524	896	4,109	3,181	0	1,926	670	12,655
Adverse birth conditions*	60	260	153	703	544	0	329	114	2,162
Total	1,327	5,745	3,388	15,038	11,892	0	7,245	2,539	47,173

*Adverse birth conditions include premature births, low birth weight and small-for-gestational-age cases.

Comparing the total benefits in each strategy, OTR4 (regular emission testing) has the highest health benefits, followed by OTR5 (shifting to public transportation) and DUST (controlling dust from construction). Figure 21 illustrates the comparison of total health benefits of each strategy.

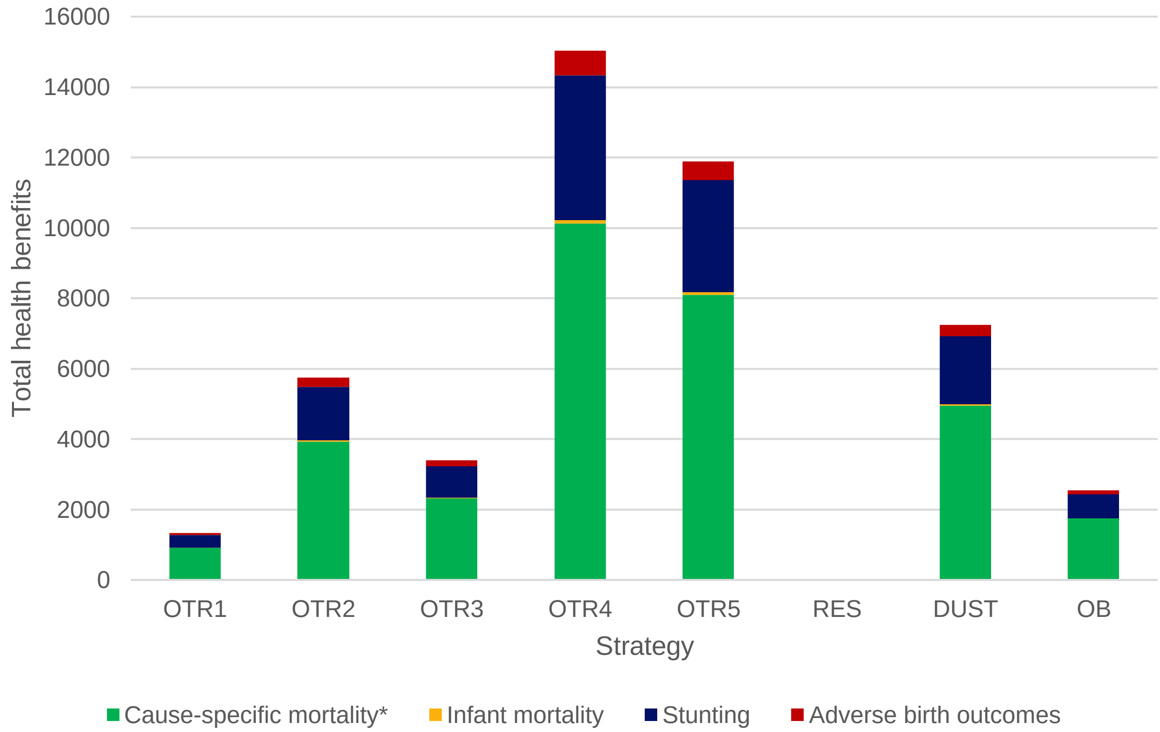


Figure 21. Considering all health benefits, OTR4 (regular emission testing) has the highest total number of health benefits, followed by OTR5 (shifting to public transportation) and DUST (controlling dust from construction). Meanwhile, RES (converting conventional stoves to electric stoves) has the fewest health benefits.

The economic value of the health impact benefits

The total benefits of air pollution reduction from the year 2019 to 2030 reached approximately US$46 billion. This is equivalent to roughly 4% of the Indonesian 2019 GDP (US$1.135 billion) or 23% of Jakarta province's 2019 GDRP (US$199 billion), as shown in Figure 22.

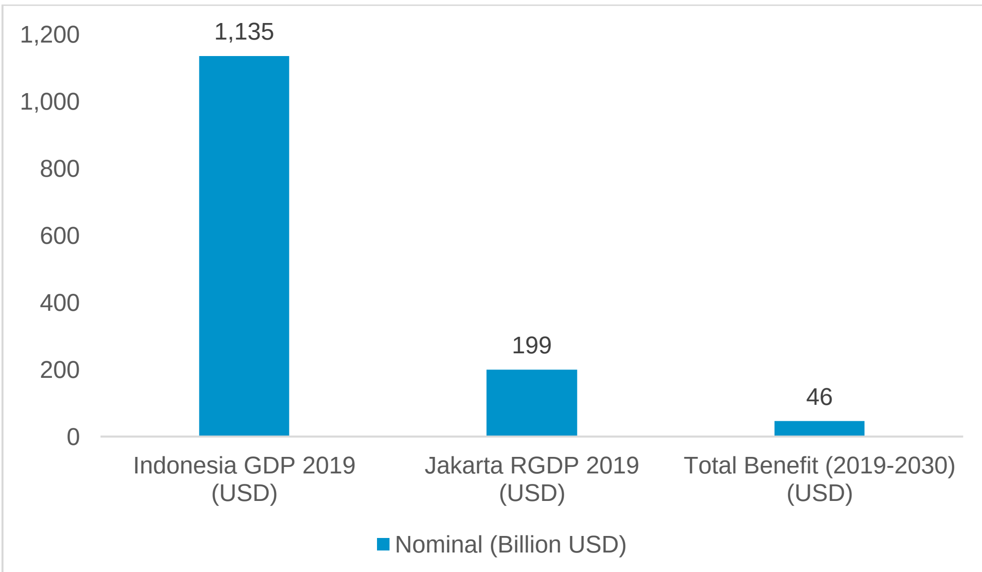


Figure 22. Annual economic value of health benefits attributable to air pollution reduction in DKI Jakarta (in billion IDR)

The benefits of averting deaths (i.e., mortality and infant deaths) consistently have the largest share of value of benefits across the interventions. Almost 98% of the total benefits per intervention is shared by the value of deaths averted, showing the large magnitude of the benefit.

Figure 23 shows the share of health benefits value per intervention. OTR4 (32%) and OTR5 (25%) are the two interventions with the highest share of health-benefit values, followed by DUST (16%). OTR1 (3%), on the other hand, has the lowest share of benefit value. Note that OTR4, OTR5 and DUST have the largest magnitude in terms of the value of benefits, as they share more than 70% of the total benefits.

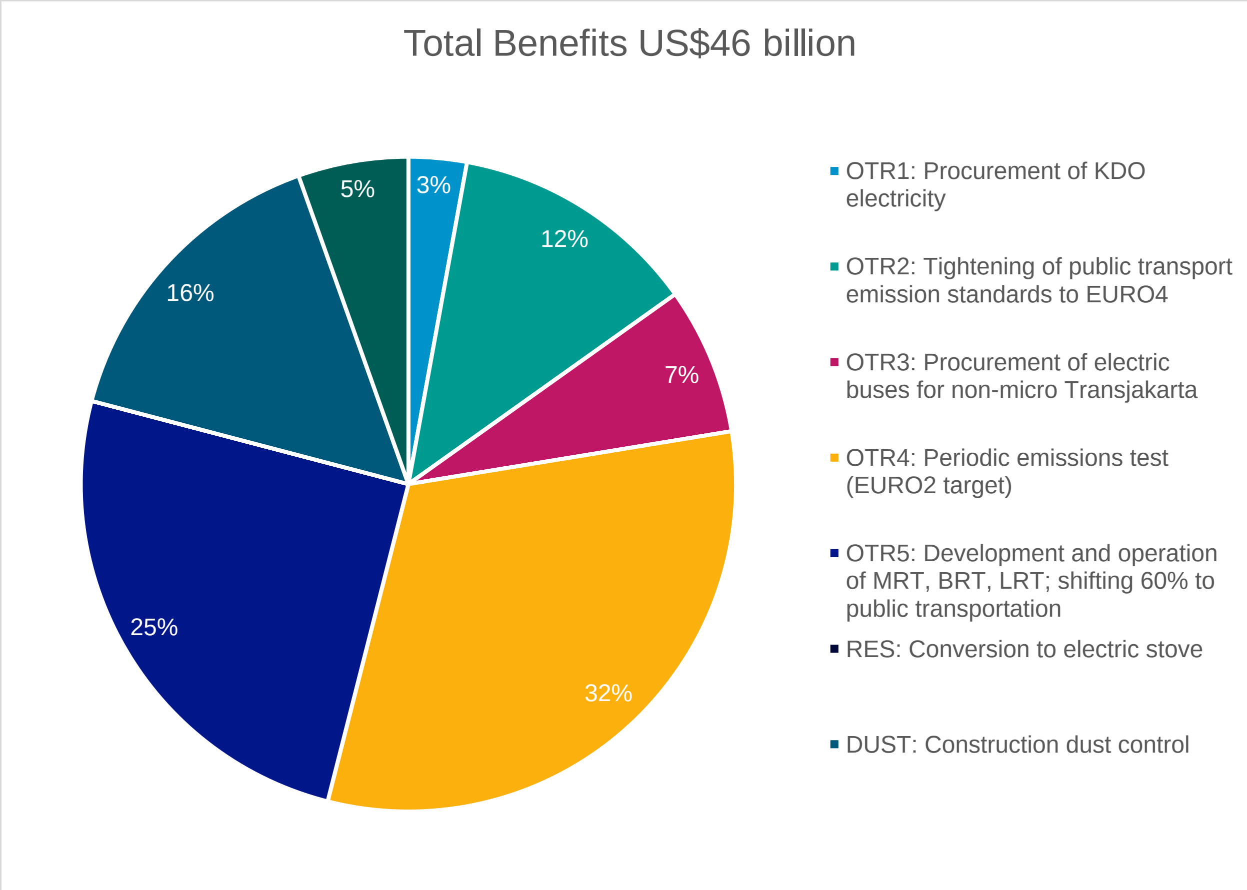


Figure 23. Share of health benefits value per intervention.

Cost benefit ratio

As shown in Table 11, the highest cost-benefit ratios come from DUST (145) and OTR1 (82). However, the largest benefit value is shown by OTR4, even though the benefit cost ratio of OTR4 is 11, as the intervention costs more. As such, in line with Figure 23, it is worth noting that OTR4 has the largest magnitude of benefit value compared to the other interventions. The total cost-benefit ratio is seven, indicating the value of the total benefit is seven times higher than its total cost (Table 10).

Table 10. Benefit cost ratio per intervention

Intervention	Cost ($000,000)	Benefit ($000,000)	B/C ratio
OTR1: Government operational electric vehicles	15.90	1,304.75	82
OTR2: Tightening of public transport emission standards to Euro 4	532.02	5,588.14	11
OTR3: Procurement of electric buses for non-micro TransJakarta	256.82	3,306.38	13
OTR4: Periodic emissions test (Euro 2 target)	1,523.77	14,356.04	9
OTR5: Development and operation of MRT, BRT, LRT; shifting 60% to public transportation	3,790.40	11,431.38	3
RES: Conversion to electric stove	562.96	-	0
DUST: Construction dust control	48.56	7,037.21	145
OB: Prohibition of open burning of garbage	77.31	2,477.15	32
Total	**6,807.74**	**45,501.06**	**7**

DISCUSSION

Our study shows a large value of benefits from interventions reducing air pollution in Jakarta province—seven times higher than the cost of the interventions. These significant benefits were explained by the high potential impacts of program implementation on $PM_{2.5}$ air quality improvement. We also found that the intervention with the largest benefit is periodic emission testing for private vehicles to comply at least with Euro 2, while the intervention with the largest cost-benefit ratio is construction dust control. Our findings lead to the following important observations.

First, the total benefit value of air pollution interventions is seven times higher than the total cost. Adjusting our mortality-averted benefit values into average yearly value using the 2019 PPP conversion factor, our finding is almost three times higher than the mortality averted value in Beijing (US$806,370 vs. US$283,106), in line with the much larger average yearly number of deaths averted (2,697 deaths vs. 797) [37]. It seems that periodic emission test intervention has the largest magnitude in terms of benefit, with the largest number of deaths averted, similar to the studies in China [38] and Brazil [39].

Second, the main programs for air pollution intervention in DKI Jakarta vary depending on one's viewpoint. If we take the cost-benefit ratio, the two programs that contribute the most, with the highest ratio, are the procurement of KDO electric vehicles and the control and monitoring of dust on construction sites. If we look at total cost, the two programs with the lowest total implementing costs are similar to the ones in the cost-benefit ratio. If we consider the total benefit, the two programs with the highest total economic benefit are the periodic emission test (Euro 2 target) and the development and operation of Mass Rapid Transit (MRT), Buss Rapid Transit (BRT) and Light Rail Transit (LRT).

Third, the total cost to implement all programs for air pollution intervention in DKI Jakarta is estimated to be IDR87.8 trillion (or US$6.3 billion), adjusting for the inflation rate in 2019. This is only around 3.12% of the total GDRP of DKI Jakarta in 2019 (IDR2,815 trillion or US$202 billion) [40]. However, if we compare the total cost to the total budget of the Environment Agency of Jakarta in 2022 [24], the total cost is 25 times the agency's total budget. This comparison suggests that the city environment agency needs more support and budget allocation from the city government to implement all air pollution strategies completely. Considering the urgency of controlling air pollution in Jakarta and the budget capacity managed by the city government in a year, this program should be feasible to implement.

Fourth, given the total economic value of the costs and benefits, we found that the benefits of pollution-reduction interventions can be seven times higher than the costs, with a few interventions having a much larger ratio. Roughly comparing them to two studies in China exploring a package of interventions to reduce air pollution [3], [41], it seems that our cost-benefit ratio is slightly higher (6.32 and 5.5 vs. 7 in our study). As such, it seems that further implementing the package of interventions in our study may be economically attractive. However, as the total cost can be quite large, interventions with the largest benefit value should be prioritized.

It is worth noting that the implementation of collective measures is encouraged, especially to achieve the target of the Grand Design for Air Pollution Control for Jakarta. The target has been set up to bring down the current annual average level of $PM_{2.5}$ to 25 $\mu g/m^3$. Modeling results show that this will not be achieved by implementing a single or a few measures. In addition, collective implementation will help maximize potential benefits, especially for human health; at the same time, cost-effectiveness will also be ensured. Meanwhile, the cost-benefit analysis, quantified for each measure, will help policymakers prioritize the program for short-, medium- and long-term planning by considering budget and other resources. It is worth noting that, due to the unavailability of emission inventory for stationary sources, our cost-benefit analysis study is developed according to mobile and area sources only.

In addition, the cost that we calculate is limited only to the priority program for air pollution intervention in DKI Jakarta. The calculation is limited to the direct costs, which are the expenses that are directly used in implementing the program. The study does not consider the indirect costs of implementing the program, such as general government expenses. We also know that the economic benefit of the implementation of labor productivity has not been considered. With these missing elements, it is likely that the results underestimate the cost-benefits of improving air quality in DKI Jakarta. The study also has uncertainties, particularly those involving making projections for future progress and performance. However, the limitations and uncertainties in this quantitative study should not deter these interventions, as most of the calculations are robust. Most importantly, improving air quality in DKI Jakarta will affect health and have associated impacts on the economy.

CONCLUSION

Our study suggests that for all programs relevant to mobile sources, $PM_{2.5}$ air quality improvement ranges from 0.5 to 5.7 µg/m^3 while emission reductions for area sources yield of 0.05-2.4 µg/m^3 (maximum annual average). Domain average concentrations of $PM_{2.5}$ improvement are within the range of 0.13-1.5 µg/m^3 (mobile sources relevant measures) and 0.01-0.7 µg/m^3 (area sources relevant measures). The collective implementation of air pollution control strategies in Jakarta will cost more than US$6 billion through 2030. However, the total benefit indicates a value seven times higher compared to the total cost of programs. The largest benefit comes from emission testing, sharing approximately 32% of the total benefit, followed by shifting to public transportation (25% of the total benefit). Collective implementation of all measures by 2030 will help anticipate increasing $PM_{2.5}$ concentrations compared to the levels measured in 2019. More aggressive measures are still required to bring down the $PM_{2.5}$ annual average levels below the NAAQS of 15 µg/m^3.

IMPLICATIONS AND RECOMMENDATIONS

In light of the findings presented in our study, it becomes evident that the emission standard compliance measure holds significant implications for society. Our study puts forth a range of recommendations that could effectively promote desired policies. First, applying emission standards is essential to ensure compliance and promote the application of clean and low-emission technologies. This can be achieved by setting stringent limits on pollutant emissions, such as nitrogen oxides (NOx), particulate matter (PM) and carbon dioxide (CO_2), and regularly updating these standards to keep pace with technologies. Through the ministry regulation PermenLHK 8/2023, Indonesia has applied emission standard updates to several types of vehicles. These standards are equivalent to Euro 4.

Second, implementing effective inspection and maintenance programs is crucial to ensure that vehicles on the road comply with standards throughout their lifespan. Regular and standardized emission testing can identify noncompliant vehicles and facilitate necessary repairs or retrofitting. An efficient inspection and maintenance program should include random roadside inspections, periodic testing for all vehicles and strict compliance enforcement. Collaborating with local automotive service providers and training them in emission control technologies can also enhance the effectiveness of inspection and maintenance programs.

Third, implementing congestion pricing and low-emission zones can promote compliance with emission standards by discouraging high-emitting vehicles. Lastly, to design more relevant air pollution control strategies in the future, recent emission inventories for both stationary and non-stationary sources are required. Therefore, having the inventories updated regularly is highly recommended.

REFERENCES

[1] L. J. Perl and F. C. Dunbar, “Cost Effectiveness and Cost-Benefit Analysis of Air Quality Regulations,” *Am Econ Rev*, vol. 72, no. 2, pp. 208–213, 1982, [Online]. Available: http://www.jstor.org/stable/1802330

[2] S. Åström, “Perspectives on using cost-benefit analysis to set environmental targets – a compilation and discussion of arguments informed by the process leading to the 2016 EU air pollution emission targets,” *Environ Impact Assess Rev*, vol. 98, p. 106941, 2023, doi: https://doi.org/10.1016/j.eiar.2022.106941.

[3] J. Gao, Z. Yuan, X. Liu, X. Xia, X. Huang, and Z. Dong, “Improving air pollution control policy in China—A perspective based on cost–benefit analysis,” *Science of The Total Environment*, vol. 543, pp. 307–314, Feb. 2016, doi: 10.1016/J.SCITOTENV.2015.11.037.

[4] L. Hsin-Chih, M.-C. Hsiao, J.-L. Liou, L.-W. Lai, P.-C. Wu, and J. Fu, “Using Costs and Health Benefits to Estimate the Priority of Air Pollution Control Action Plan: A Case Study in Taiwan,” *Applied Sciences*, vol. 10, p. 5970, Aug. 2020, doi: 10.3390/app10175970.

[5] X. Liu *et al.*, “Evaluating cost and benefit of air pollution control policies in China: A systematic review,” *Journal of Environmental Sciences*, vol. 123, pp. 140–155, 2023, doi: https://doi.org/10.1016/j.jes.2022.02.043.

[6] Y. Chae and J. Park, “Quantifying costs and benefits of integrated environmental strategies of air quality management and greenhouse gas reduction in the Seoul Metropolitan Area,” *Energy Policy*, vol. 39, no. 9, pp. 5296–5308, 2011, doi: https://doi.org/10.1016/j.enpol.2011.05.034.

[7] LPPM Itenas, Vital Strategies, and Dinas Lingkungan Hidup DKI Jakarta, “Studi perhitungan skenario penurunan emisi pencemar udara untuk Provinci DKI Jakarta,” Bandung, 2021.

[8] A. Venkatram and W. Qian, "Regulatory Modelling: Current and Future Issues," *Air Quality and Climate Change*, vol. 43, no. 4, pp. 17–23, 2009.

[9] Nurhayati-Wolff H, "Annual Inflation Rate of the Healthcare Sector in Indonesia from 2014 to 2020.," https://www.statista.com/statistics/1005580/indonesia-annual-inflation-rate-of-healthcare/#statisticContainer.

[10] Statistics DKI Jakarta, "Statistik Transportasi Provinsi DKI Jakarta 2020," Jakarta, Nov. 2021. [Online]. Available: https://jakarta.bps.go.id/publication/2021/11/23/1aaaa91a6dd67d24ffeed6cd/statistik-transportasi-provinsi-dki-jakarta-2020.html

[11] Kompas, "Dishub DKI Anggarkan Rp 119 Miliar untuk Kendaraan Dinas, Termasuk Motor Listrik ," Jakarta, 2022. Accessed: Mar. 25, 2023. [Online]. Available: https://megapolitan.kompas.com/read/2022/11/12/06103631/dishub-dki-anggarkan-rp-119-miliar-untuk-kendaraan-dinas-termasuk-motor#

[12] Statistics DKI Jakarta, "Statistik Transportasi DKI Jakarta 2016," Jakarta, Oct. 2017. [Online]. Available: https://jakarta.bps.go.id/publication/2017/10/11/306f08af1cacc7446e818011/statistik-transportasi-dki-jakarta-2016.html

[13] Government of Indonesia, "Instruksi Presiden (INPRES) Nomor 7 Tahun 2022 tentang Penggunaan Kendaraan Bermotor Listrik Berbasis Baterai (Battery Electric Vehicle) Sebagai Kendaraan Dinas Operasional dan/atau Kendaraan Perorangan Dinas Instansi Pemerintah Pusat dan Pemerintahan Daerah," 2022. [Online]. Available: https://peraturan.bpk.go.id/Home/Details/225262/inpres-no-7-tahun-2022

[14] Statistics DKI Jakarta, "Statistik Transportasi DKI Jakarta 2019," Jakarta, Oct. 2020. [Online]. Available: https://jakarta.bps.go.id/publication/2020/10/30/5334ef6b5ef39c73ec068416/statistik-transportasi-dki-jakarta-2019.html

[15] Ministry of Energy and Mineral Resources, "Indonesia Energy Outlook 2019," Jakarta, Sep. 2019. [Online]. Available: https://www.esdm.go.id/assets/media/content/content-indonesia-energy-outlook-2019-english-version.pdf

[16] Statistics DKI Jakarta, “Jumlah Kendaraan Bermotor Menurut Provinsi dan Jenis Kendaraan (unit), 2022.” [Online]. Available: https://www.bps.go.id/indikator/indikator/view_data_pub/0000/api_pub/V2w4dFkwdFNLNU5mSE95Und2UDRMQT09/da_10/1

[17] C40 Cities Finance Facility, “Procurement of E-Buses (BRT Routes) by TransJakarta,” Germany, 2021. [Online]. Available: https://cff-prod.s3.amazonaws.com/storage/files/GMYXvg2BuYxwtf7gLh3X0RRfZq2oulLeEPjQ1r53.pdf

[18] Statistics DKI Jakarta, “Statistik Transportasi Provinsi DKI Jakarta 2021,” Jakarta, Nov. 2022. [Online]. Available: https://jakarta.bps.go.id/publication/2022/11/23/7afbea4e4bffe82f2c3e2d7a/statistik-transportasi-provinsi-dki-jakarta-2021.html

[19] Kompas, “Tarif Integrasi Rp 10.000 Berlaku di Semua Halte Transjakarta.” Accessed: Apr. 04, 2023. [Online]. Available: https://megapolitan.kompas.com/read/2022/08/12/16445101/tarif-integrasi-rp-10000-berlaku-di-semua-halte-transjakarta?page=all

[20] PT Transportasi Jakarta, “Laporan Tahunan TransJakarta.” Accessed: Feb. 15, 2023. [Online]. Available: https://ppid.transjakarta.co.id/informasi-publik/laporan-tahunan-pt-transportasi-jakarta

[21] Indonesian Railways Company, “Rencana Kerja dan Anggaran Perusahaan Tahun 2022,” Jakarta, 2022. [Online]. Available: https://ppid.kai.id/media/konten/111_rka.pdf

[22] Statistics DKI Jakarta, “Statistik Tranportasi DKI Jakarta 2018,” Jakarta, 2019. [Online]. Available: https://jakarta.bps.go.id/publication/2018/10/03/cb1285d8dbe8be8754a5830d/statistik-transportasi-dki-jakarta-2018.html

[23] Statistics DKI Jakarta, “Jumlah Rumah Tangga menurut Kabupaten/Kota di Provinsi DKI Jakarta 2020-2022.” Accessed: Apr. 05, 2023. [Online]. Available: https://jakarta.bps.go.id/indicator/12/1055/1/jumlah-rumah-tangga-menurut-kabupaten-kota-di-provinsi-dki-jakarta.html

[24] Jakarta Environment Agency, “Data Program dan Anggaran Dinas Lingkungan Hidup DKI Jakarta 2020 - 2022.” Accessed: Apr. 03, 2023. [Online]. Available: https://lingkunganhidup.jakarta.go.id/program/anggaran

[25] Badan Pusat Statistik and Bappenas, "Proyeksi Penduduk Indonesia 2015-2045 Hasil SUPAS 2015-2045," Jakarta, Indonesia, 2018.

[26] C. Abbafati *et al.*, "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*, vol. 396, no. 10258, pp. 1223–1249, Oct. 2020, doi: 10.1016/S0140-6736(20)30752-2.

[27] G. Syuhada *et al.*, "Impacts of Air Pollution on Health and Cost of Illness in Jakarta, Indonesia," *Int J Environ Res Public Health*, vol. 20, p. 2916, Feb. 2023, doi: 10.3390/ijerph20042916.

[28] S. Heft-Neal, J. Burney, E. Bendavid, and M. Burke, "Robust relationship between air quality and infant mortality in Africa," *Nature*, vol. 559, no. 7713, pp. 254–258, 2018, doi: 10.1038/s41586-018-0263-3.

[29] V. C. Pun, R. Dowling, and S. Mehta, "Ambient and household air pollution on early-life determinants of stunting—a systematic review and meta-analysis," *Environmental Science and Pollution Research*, vol. 28, no. 21, pp. 26404–26412, 2021, doi: 10.1007/s11356-021-13719-7.

[30] Y. Liu, J. Xu, D. Chen, P. Sun, and X. Ma, "The association between air pollution and preterm birth and low birth weight in Guangdong, China," *BMC Public Health*, vol. 19, no. 1, p. 3, 2019, doi: 10.1186/s12889-018-6307-7.

[31] H. Nurhayati-Wolff, "Annual Inflation Rate of the Healthcare Sector in Indonesia from 2014 to 2020," Statista. Accessed: Sep. 10, 2021. [Online]. Available: https://www.statista.com/statistics/1005580/indonesia-annual-inflation-rate-of-healthcare/#statisticContainer

[32] L. A. Robinson, J. K. Hammitt, and L. O'Keeffe, "Valuing mortality risk reductions in global benefit-cost analysis," *J Benefit Cost Anal*, vol. 10, pp. 15–50, Jan. 2019, doi: 10.1017/bca.2018.26.

[33] J. Hoddinott, H. Alderman, J. R. Behrman, L. Haddad, and S. Horton, "The economic rationale for investing in stunting reduction," *Matern Child Nutr*, vol. 9, pp. 69–82, Sep. 2013, doi: 10.1111/mcn.12080.

[34] Government of DKI Jakarta, "Data Kendaraan Dinas Operasional Di Provinsi DKI Jakarta," Jakarta, 2018. [Online]. Available: https://data.jakarta.go.id/dataset/data-kendaraan-dinas-operasional-di-dki-jakarta

[35] Statistics DKI Jakarta, “Jumlah Pegawai Negeri Sipil Menurut Provinsi/Kabupaten/Kota dan Jenis Kelamin 2019-2022.” Accessed: Apr. 03, 2023. [Online]. Available: https://jakarta.bps.go.id/indicator/101/389/1/jumlah-pegawai-negeri-sipil-menurut-provinsi-kabupaten-kota-dan-jenis-kelamin.html

[36] Informasi Biaya, “Biaya Perpanjangan KIR Kendaraan & Pengujian,” Jakarta, Aug. 2020. Accessed: Mar. 20, 2023. [Online]. Available: https://biaya.info/biaya-perpanjangan-kir-kendaraan-pengujian/

[37] N. Zhao *et al.*, “The efforts of China to combat air pollution during the period of 2015–2018: a case study assessing the environmental, health and economic benefits in the Beijing-Tianjin-Hebei and surrounding ‘2 + 26’ regions,” *Science of The Total Environment*, vol. 853, no. August, p. 158437, Dec. 2022, doi: 10.1016/j.scitotenv.2022.158437.

[38] Y.-H. Liu, W.-Y. Liao, X.-F. Lin, L. Li, and X. Zeng, “Assessment of co-benefits of vehicle emission reduction measures for 2015–2020 in the Pearl River Delta region, China,” *Environmental Pollution*, vol. 223, no. 2017, pp. 62–72, Apr. 2017, doi: 10.1016/j.envpol.2016.12.031.

[39] L. M. Baptista Ventura, F. de Oliveira Pinto, A. Gioda, and M. de Almeida D’Agosto, “Inspection and maintenance programs for in-service vehicles: an important air pollution control tool,” *Sustain Cities Soc*, vol. 53, p. 101956, Feb. 2020, doi: 10.1016/j.scs.2019.101956.

[40] Statistics DKI Jaka, “PDRB Provinsi Atas Dasar Harga Berlaku menurut Pengeluaran (Milyar Rupiah), 2017-2019.” Accessed: Mar. 04, 2023. [Online]. Available: https://jakarta.bps.go.id/indicator/156/63/2/pdrb-provinsi-atas-dasar-harga-berlaku-menurut-pengeluaran-.html

[41] J. Zhang *et al.*, “Cost-benefit analysis of China’s action plan for air pollution prevention and control,” *Frontiers of Engineering Management*, vol. 6, no. 4, pp. 524–537, Dec. 2019, doi: 10.1007/s42524-019-0074-8.

SUPPLEMENTS

Supplement 1: References for assumptions used to estimate the cost of programs

Program	Item	Unit	Value	Reference
OTR1	Number of EV: motorcycle 2023	unit	110	https://megapolitan.kompas.com/read/2022/11/12/06103631/dishub-dki-anggarkan-rp-119-miliar-untuk-kendaraan-dinas-termasuk-motor#
	Budget for EV motorcycles 2023	mil IDR	4400	https://megapolitan.kompas.com/read/2022/11/12/06103631/dishub-dki-anggarkan-rp-119-miliar-untuk-kendaraan-dinas-termasuk-motor#
	Number of government vehicles	unit	322	https://data.jakarta.go.id/dataset/data-kendaraan-dinas-operasional-di-dki-jakarta
	Growth of government vehicles: car	%	0.5	Assumption based on the number of civil servants
	Growth of government vehicles: motorcycle	%	1	Assumption based on the number of civil servants
	Projection of government vehicles	trend	linear	Historic trend
	Price of EV: car	mil IDR	299.5	https://wuling.id/id/daftar-harga?gclid=CjwKCAiA_6yfBhBNEiwAkmXy50huophgVfhK0qSC1zehC7_2ApnEG62r1-A8B5svwqUv61oa_UE1YBoCZnMQAvD_BwE
	Price of EV: motorcycle	mil IDR	10.3	https://shopee.co.id/Sepeda-Motor-Listrik-T3-Uwinfly-1200W-Garansi-Resmi-Bonus-Helm-i.171924225.18753757512?sp_atk=3e27339b-5298-49cf-9883-

				9ca8c21e55c6&xptdk=3e27339 b-5298-49cf-9883-9ca8c21e55c6
	Operational cost per unit conv gov vehicle	mil IDR	5	Own assumption
	Operational cost per unit EV	mil IDR	10	Own assumption
OTR2	Number of public transportations 2019	unit	35,602	Statistics Office DKI Jakarta 2019
	Growth of public transport	%	-8.12	Statistics Office DKI Jakarta 2016-2019
	Steady state growth	year	2025	Own assumption
	Projection of public transport	trend	linear	Historical trend
	Price of solar Dexlite CN51	IDR	17,100	https://www.cnbcindonesia.com/news/20220924062439-4-374615/daftar-lengkap-harga-bbm-indonesia-spbu-swasta-turun-harga
	Price of BioSolar CN48	IDR	6,800	https://www.cnbcindonesia.com/news/20220924062439-4-374615/daftar-lengkap-harga-bbm-indonesia-spbu-swasta-turun-harga
	Share DKI to national: solar use	%	15	https://www.bps.go.id/indikator/indikator/view_data_pub/0000/api_pub /V2w4dFkwdFNLNU5mSE95Und2UDRMQT09/da_10/1
	Share public transport to transportation sector	%	10	Statistics Office DKI Jakarta 2019
	Solar demand national (average)	mil kliter	14.79	https://dataindonesia.id/sektor-riil/detail/konsumsi-solar-di-indonesia-capai-159-juta-kiloliter-pada-2021
	Oil price growth	%	10	Own assumption

	Price of emission test for public transport	IDR	87,000	https://biaya.info/biaya-perpanjangan-kir-kendaraan-pengujian/
OTR3	Price of electric bus	mil IDR	5,000	C40 Cities Finance Facility Report
	Projection of electric bus	trend	linear	Own assumption
	Rate of maintenance	%	7.5	Own assumption
OTR4	Number of private cars 2019	unit	2,805,989	https://statistik.jakarta.go.id/peningkatan-jumlah-kendaraan-bermotor-di-dki-jakarta/
	Number of private motorcycles 2019	unit	8,194,590	https://statistik.jakarta.go.id/peningkatan-jumlah-kendaraan-bermotor-di-dki-jakarta/
	Projection of private vehicle	trend	linear	Historical trend
	Growth of private cars	%	2.59	Statistics Office 2017-2019
	Growth of private motorcycles	%	4.11	Statistics Office 2017-2019
	Operational cost per unit	IDR	127,764	https://databoks.katadata.co.id/datapublish/2022/02/23/capaian-uji-emisi-kendaraan-di-jakarta-masih-sangat-rendah
	Rate of maintenance	%	7.5	Own assumption
OTR5	Multiplier for car	power	2	Own assumption
	Multiplier for motorcycle	power	1	Own assumption
	Transportation cost per day for KRL/Transjakarta	IDR	10,000	https://megapolitan.kompas.com/read/2022/08/12/16445101/tarif-integrasi-rp-10000-berlaku-di-semua-halte-Transjakarta?page=all
	Coverage for subsidy	%	50-25	Own assumption
	Projection of number people shifting to public transport	trend	exponential	Historical trend

	Projection of KRL passenger	trend	logarithmic	Historical trend
	Projection of Transjakarta passenger	trend	logarithmic	Historical trend
	Growth of total revenue KRL	%	15.88	https://ppid.kai.id/media/konten/111_rka.pdf
	Growth of total revenue Transjakarta	%	28.66	https://jakarta.bps.go.id/indicator/17/812/1/jumlah-penumpang-dan-pendapatan-trans-jakarta-menurut-koridor-rute.html
	Share operational cost to total revenue KRL/Transjakarta	%	80	Own assumption
	Rate of maintenance	%	7.5	Own assumption
RES	Number of HH 2021	HH	2,770,729	https://jakarta.bps.go.id/subject/12/kependudukan.html#subjekViewTab3
	Projection of number of households	trend	exponential	Historical trend
	Subsidy per HH	mil IDR	2.5	https://katadata.co.id/happyfajrian/berita/63368520ac369/rencana-pembagian-10000-kompor-listrik-gratis-di-jakarta-kandas
	Rate of maintenance	%	7.5	Own assumption
DUS	Budget for controlling 2022	mil IDR	256.65	https://lingkunganhidup.jakarta.go.id/program/anggaran
	Number of firms 2020	unit	1721	https://jakarta.bps.go.id/indicator/9/226/1/jumlah-perusahaan-tenaga-kerja-investasi-dan-nilai-produksi-pada-industri-besar-dan-sedang-menurut-kabupaten-kota.html
	Operational cost per unit	%	10	Own assumption
	Rate of maintenance	%	7.5	Own assumption
OB	Budget for controlling 2022	mil IDR	544.67	https://jakarta.bps.go.id/indicator/9/226/1/jumlah-perusahaan-

				tenaga-kerja-investasi-dan-nilai-produksi-pada-industri-besar-dan-sedang-menurut-kabupaten-kota.html
	Number of HH per cluster	HH	1000	Own assumption
	Operational cost per cluster	mil IDR	16	Own calculation
	Rate of maintenance	%	7.5	Own assumption

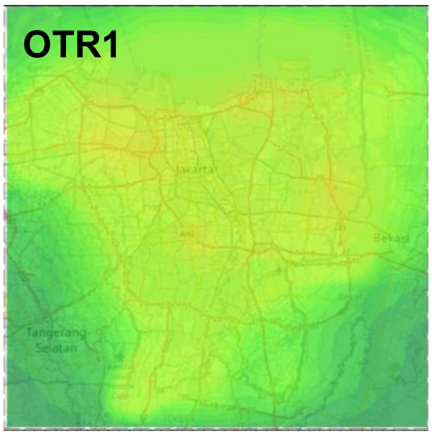
Supplement 2: Outcome definition

The following table describes the definition of health outcomes assessed in this study. For the cause-specific mortality, the disease groups are in accordance with the ICD-10 categorization used in the GBD 2019 Study.

Supplementation Table 1. Summary of health outcomes and their definition included in the study

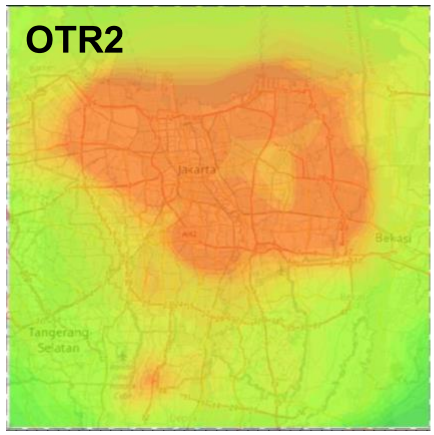
Outcome	Definition (ICD-10 or otherwise specified)
Children health outcomes	
• Infant mortality	All cause
• Stunting	Height for age less than two standard deviations of the WHO Child Growth Standards median
Adverse birth outcomes	
• Low birth weight, at term	Weight <2,500 g at birth after 37 weeks of gestation
• Preterm birth	Birth at the gestation of <37 weeks
• Small for gestational age	Weight <10th percentile of infant born at given gestational age
Cause-specific mortality	
• Ischemic heart disease	I20–I25
• Cerebrovascular disease (stroke)	I60–I63, I65–I67, I69.0–I69.3
• Chronic obstructive pulmonary disease (COPD)	J40–J44, J47
• Type 2 diabetes mellitus	E10–E13
• Trachea, bronchus, and lung cancer	C33–C34. D02.1, D02.2, D38.1
• Lower respiratory infections	J09–J15.8, J16–J16.9, J20–J21.9, P23-P23.9, and Z25.1

Supplement 3: Simulation results for the year 2025 (in µg/m^3)



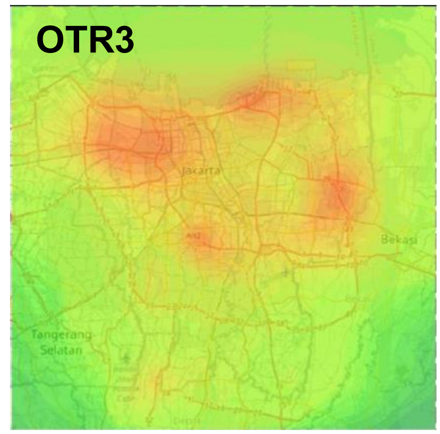
Domain average: 0.12

Domain max: 0.46



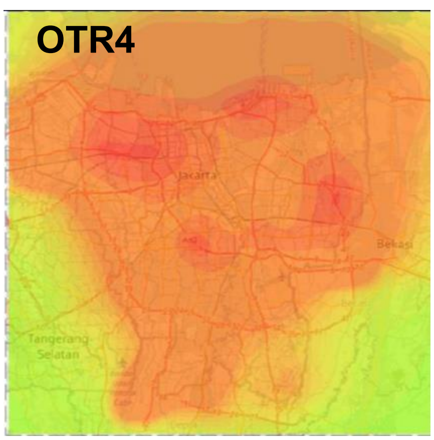
Domain average: 0.53

Domain max: 2



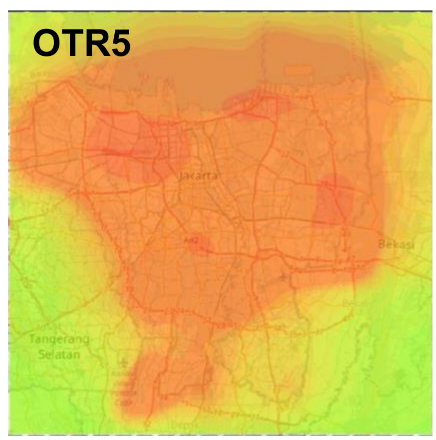
Domain average: 0.3

Domain max: 1.2



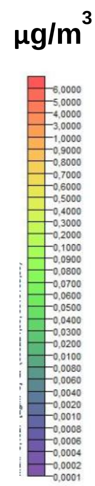
Domain average: 1.4

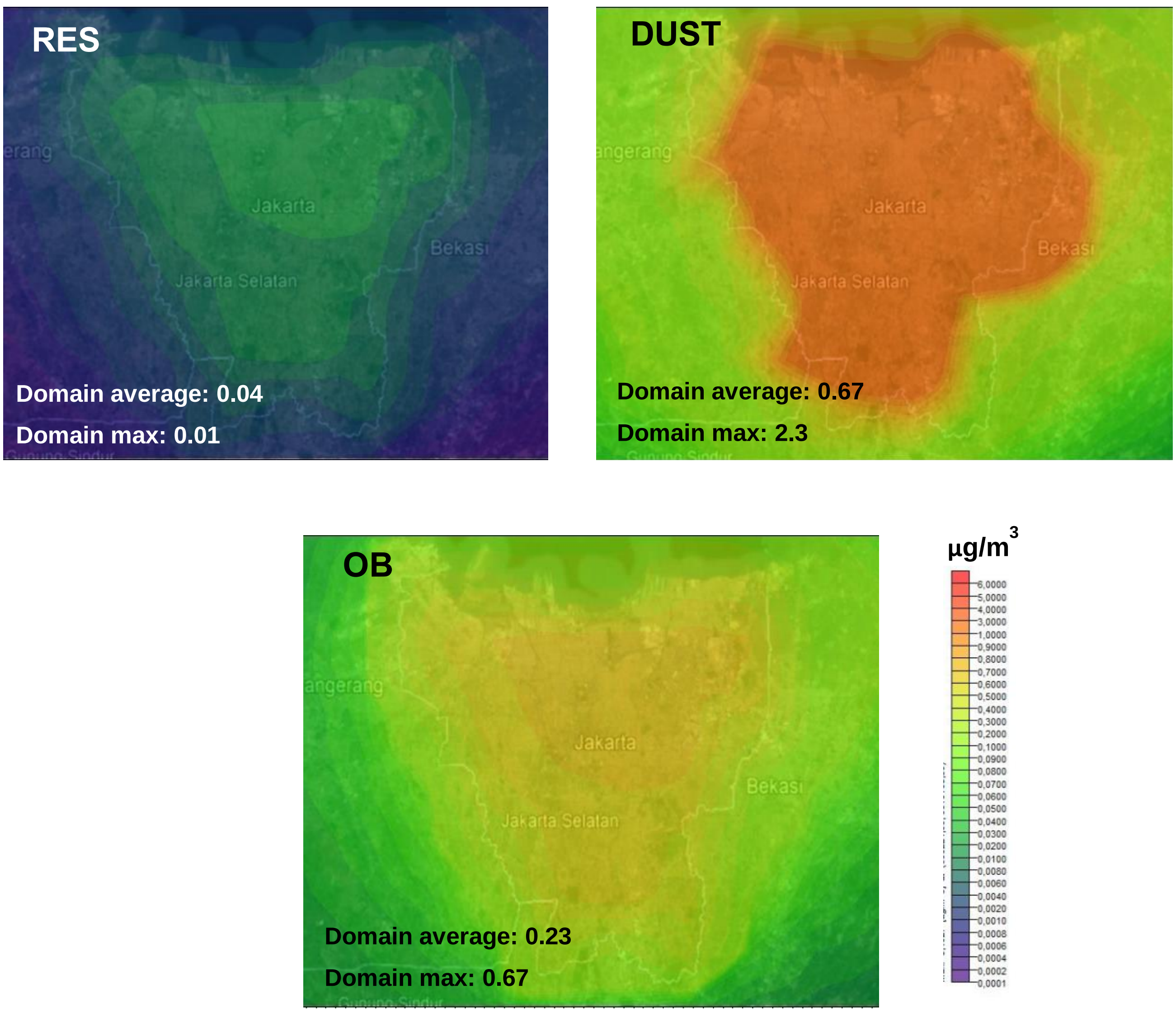
Domain max: 5.4



Domain average: 1.1

Domain max: 4.1




RES
Jakarta
Bekasi
Jakarta Selatan
Domain average: 0.04
Domain max: 0.01
DUST
Jakarta
Bekasi
Jakarta Selatan
Domain average: 0.67
Domain max: 2.3
OB
Jakarta
Bekasi
Jakarta Selatan
Domain average: 0.23
Domain max: 0.67
µg/m3
6,0000
5,0000
4,0000
3,0000
1,0000
0,9000
0,8000
0,7000
0,6000
0,5000
0,4000
0,3000
0,2000
0,1000
0,0900
0,0800
0,0700
0,0600
0,0500
0,0400
0,0300
0,0200
0,0100
0,0080
0,0060
0,0040
0,0020
0,0010
0,0008
0,0006
0,0004
0,0002
0,0001