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Air pollution mitigation assessment to inform Cambodia's first clean air plan

Pak Sokharavuth [a], Sophearith Thiv [a], Chea Nara [a], Chandath Him [b], Sam Sokyimeng [b], Daven K. Henze [c], Ryan Holmes [d], Johan C.I. Kuylenstierna [d], Christopher S. Malley [d,*], Eleni Michalopoulou [d], Jessica Slater [d]

[a] General Directorate of Environmental Protection, Ministry of Environment, Phnom Penh, Cambodia
[b] Air Quality and Noise Management Department, Ministry of Environment, Phnom Penh, Cambodia
[c] Department of Mechanical Engineering, University of Colorado, Boulder, CO, United States
[d] Stockholm Environment Institute, Department of Environment and Geography, University of York, United Kingdom

A R T I C L E I N F O

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A B S T R A C T

Cambodia's 16.5 million people are exposed to air pollution in excess of World Health Organisation guidelines. The Royal Government of Cambodia has regulated air pollutant emissions and concentrations since 2000, but rapid economic growth and energy consumption means air pollution continues to impact human health. In December 2021, the Ministry of Environment of Cambodia published Cambodia's first Clean Air Plan that outlines actions to reduce air pollutant emissions over the next decade. This work presents the quantitative air pollution mitigation assessment underpinning the identification and evaluation of measures included in Cambodia's Clean Air Plan. Historic emissions of particulate matter ($PM_{2.5}$, black carbon, organic carbon) and gaseous (nitrogen oxides, volatile organic compounds, sulphur dioxide, ammonia, and carbon monoxide) air pollutants are quantified between 2010 and 2015, and projected to 2030 for a baseline scenario. Mitigation scenarios reflecting implementation of 14 measures included in Cambodia's Clean Air Plan were modelled, to quantify the national reduction in emissions, from which the reduction in ambient $PM_{2.5}$ exposure and attributable health burdens were estimated. In 2015, the residential, transport, and waste sectors contribute the largest fraction of national total air pollutant emissions. Without emission reduction measures, air pollutant emissions could increase by between 50 and 150% in 2030 compared to 2015 levels, predominantly due to increases in transport emissions. The implementation of the 14 mitigation measures could substantially reduce emissions of all air pollutants, by between 60 and 80% in 2030 compared to the baseline. This reduction in emissions was estimated to avoid approximately 900 (95% C.I.: 530–1200) premature deaths per year in 2030 compared to the baseline scenario. In addition to improving air pollution and public health, Cambodia's Clean Air Plan could also to lead to additional benefits, including a 19% reduction in carbon dioxide emissions, simultaneously contributing to Cambodia's climate change goals.

1. Introduction

Cambodia is a lower-middle income country in southeast Asia with a population of 16.5 million. In 2021, its GDP per capita was of $1500 per person (2021 USD), almost double 2010 levels (World Bank, 2021). As a consequence of this economic development, and the concurrent increases in fuel combustion, industrial and other activity, concentrations of air pollutants exceed World Health Organisation guidelines for the protection of human health. Population-weighted annual exposure to ambient fine particulate matter ($PM_{2.5}$) is estimated to be 22.1 μg m^{-3} in 2019 (Health Effects Institute, 2020), more than four times the WHO guideline for annual average fine particulate matter ($PM_{2.5}$) concentrations (WHO, 2021). This level of exposure is estimated to be associated with a substantial health burden, with 17,000 premature deaths in 2019 in Cambodia attributed to ambient and household $PM_{2.5}$ exposure (Murray et al., 2020).

The Royal Government of Cambodia has had in place legislation to monitor and reduce air pollutant emissions since 2000. Sub-decree No.

* Corresponding author.
E-mail address: chris.malley@york.ac.uk (C.S. Malley).

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42 on the control of air pollution and noise disturbance, passed in 2000, empowers the Ministry of Environment of Cambodia to regulate air pollutant emissions (The Royal Government of Cambodia, 2000). The Ministry of Environment also has the responsibility for monitoring air pollutant concentrations, and for notifying and communicating to the public any levels of air pollution 'which may threaten human life or environmental quality'. The sub-decree also establishes ambient air quality standards for the protection of human health for carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ozone (O_3), lead (Pb), and Total Suspended Particulates (TSP). These ambient air quality standards have not been updated in Cambodia since 2000. Due to greater evidence for the impacts of air pollution on human health, the level and pollutants covered by these standards do not fully protect against the negative health impacts of air pollution. For example, for particulate matter air pollution, $PM_{2.5}$ is the most common metric used to monitor and assess particulate matter levels in the atmosphere and their relevance to human health, but is not included within the Sub-decree No. 42 standards (WHO, 2021).

Since 2000, the growth of the national economy has increased activity in key air pollutant emission sources including the number of vehicles, fuel consumption in industries and business, agricultural production, and waste generation. As a result, in 2020, the Prime Minister, on behalf of the Royal Government of Cambodia issued a 'Circular on the Strategies to Prevent and Reduce Ambient Air Pollution' (hereafter referred to as the Circular) (The Royal Government of Cambodia, 2020). This Circular acknowledged that the growth of Cambodia's economy has resulted in air pollutant levels that pose a risk to public health. The Circular outlines specific actions that ministries, institutions and sub-national governments should work to implement to reduce air pollutant concentrations, in particular $PM_{2.5}$. However, the actions included in the Circular were not quantitatively evaluated to assess their contribution to reducing emissions, or exposure in Cambodia.

Between 2020 and 2021, the Air Quality and Noise Management Department of the Ministry of Environment of Cambodia collaborated with the United Nations Environment Programme to develop Cambodia's first Clean Air Plan (Ministry of Environment of Cambodia, 2022). Cambodia's Clean Air Plan aimed to provide the first comprehensive assessment of how Cambodia can reduce air pollution and its associated health impacts, based on a robust, quantitative assessment of mitigation actions. The Clean Air Plan includes a set of actions to improve air quality in Cambodia, including those outlined in the 2020 Air Pollution Circular. Cambodia also has a range of other plans and strategies that have the potential to affect air pollutant emissions. For example, Cambodia's climate change mitigation commitments, including its Nationally Determined Contribution (NDC) includes measures such as expanding renewable electricity generation that will not only reduce greenhouse gases (GHGs), but could simultaneously reduce air pollutants.

This paper describes the quantitative air pollution mitigation assessment for Cambodia that was the basis for the development of Cambodia's first Clean Air Plan, which was endorsed and published by the Ministry of Environment of Cambodia in January 2022. This quantitative assessment of air pollution mitigation first develops a comprehensive national historic (2010–2015) emission inventory of key air pollutants. Emissions are then projected for a baseline scenario (2016–2030) based on expected socioeconomic development in Cambodia, but without implementation of policies and measures designed to reduce emissions. Thirdly, alternative future scenarios reflecting the implementation of specific mitigation measures are modelled, to assess the reduction in air pollutant emissions that could result from their implementation. Finally, an initial assessment is made of the reductions in population-weighted $PM_{2.5}$ exposure, and associated health impacts are estimated that could be achieved from implementing all mitigation measures included in Cambodia's Clean Air Plan.

2. Methodology

The air pollutant mitigation assessment was developed between 2019 and 2021 within a planning process in which inputs were gathered from key stakeholders including the Ministries, Departments and Agencies responsible for major emitting source sectors. This facilitated access to key data, and identification, evaluation and endorsement of assumptions and emission reductions from the mitigation measures evaluated. Section 2.1 describes the overall modelling framework within which the analysis was developed. Section 2.2 outlines the sector-specific methods, data and assumptions used to quantify historic and future baseline emissions, based on expected socio-economic development in Cambodia. Finally, Section 2.3 describes how the emission reduction potential of specific mitigation measures were quantified to evaluate their reduction in air pollutant emissions.

2.1. Overall modelling framework

The air pollutant mitigation assessment was implemented using the Low Emissions Analysis Platform (LEAP) software (Heaps, 2020). It covers all anthropogenic air pollutant emitting sectors, categorised into four overarching categories, i) Energy, ii) Industrial Processes and Product Use (IPPU), iii) Agriculture, and iv) Waste. From these sources, the mitigation assessment quantifies emissions of air pollutants that contribute to the formation of $PM_{2.5}$ (primary emitted $PM_{2.5}$ components and gaseous $PM_{2.5}$ precursors), and ozone (O_3) in the atmosphere, specifically black carbon (BC), organic carbon (OC), primary $PM_{2.5}$, primary PM_{10}, non-methane volatile organic compounds (VOCs), nitrogen oxides (NO_x), ammonia (NH_3), sulphur dioxide (SO_2), and carbon monoxide (CO). To assess the co-benefits from actions to reduce air pollution for climate change, emissions of carbon dioxide (CO_2) were also quantified for all emission sources included in the analysis. Air pollutant and CO_2 emissions from Forestry and Other Land Use (FOLU) were not quantified within this assessment. Forest and other vegetation fires can be sources of air pollutant emissions in South East Asia (UNEP, 2019). However, these and other natural air pollutant emission sources were not included in the mitigation assessment, or Cambodia's Clean Air Plan, where mitigation measures focused on major anthropogenic source sectors.

Emissions were estimated for two time periods, i) historic years between 2010 and 2015, and ii) future projections from 2016 to 2030. For some sources (described below), more recent historical data was available for years after 2015, and was integrated into the analysis. The historical years include a single estimate of annual national emissions based on historical data. For future projections, first a baseline scenario was developed which reflects expected population growth and economic projections, which are used as drivers of activity in key air pollution emitting source sectors. Secondly, mitigation scenarios were developed which represent the implementation of individual mitigation measures identified in national plans and strategies to assess their air pollutant emission reduction potential. Finally, aggregate mitigation scenarios were developed to estimate future emissions after implementation of groups of mitigation measures, to assess the overall emission reductions. These scenarios account for interactions between the implementation of different mitigation measures. For example, the overall impact on emissions of implementing energy efficiency measures in energy demand sectors to reduce electricity demand, alongside expansion of renewable electricity generation are different to the sum of implementing these measures individually.

2.2. Sector-specific modelling of historic emissions and baseline projections to 2030

For historical years, air pollutant emission estimates were calculated by multiplying specific activity data by emission factors. In general, and where possible, the activity data used for each sector was extracted from relevant national reports or data obtained from the sectoral Ministry responsible for that sector. In some cases, international data sources were used when national data was not available. In contrast, for the majority of sectors, default international emission factors were combined with the activity data, due to a lack of country-specific emission factors developed in Cambodia. For most air pollutant emission sources, emission factors from the EMEP/EEA national air pollutant emission inventory guidebook were used (EMEP/EEA, 2019). While designed to facilitate air pollutant emission reporting in Europe, it has also been recommended as a source of emission factors globally where better emission factors are not available. However, for some major air pollutant emission sources, i.e. biomass combustion in Residential, Waste, and Charcoal Production, more globally representative emission factors reported in Akagi et al. (2011) were used. The full set of emission factors used in the analysis are available at: https://leap.sei.org/default.asp?action=IBC. The methods and data sources used for historical emissions are summarised in Table 1, and described in more detail in the following sub-sectors.

For future years, the baseline scenario provides a reference against which the emission reduction potential of different mitigation measures could be evaluated and was designed to reflect the current development trajectories in Cambodia. For each sector, the activity variables outlined in Table 1 were linked to a particular driver to project how the magnitude of that variable would change over time between 2016 and 2030. The key socioeconomic statistics projected for Cambodia are summarised in Table 2, and the drivers for each sector are summarised in Table 3.

The following sub-sections describe the sector specific data, assumptions and methodologies used to quantify historic and future GHG emissions in those sectors.

2.2.1. Energy sector

An energy system model was developed that linked energy demand and supply. The energy demand module quantified historic and future consumption of solid (e.g. wood, charcoal), liquid (e.g. gasoline, diesel, kerosene, heavy fuel oil, liquified petroleum gas (LPG)) and gaseous (e.g. natural gas) fuels, and electricity. The consumption of these fuels and electricity were disaggregated into five sectors, Residential, Commercial and Public Services, Industry, Agriculture and Transport. In the energy demand modules, where air pollutants are emitted at the point of consumption (i.e. through combustion of the fuel), the quantity of fuel consumed were multiplied by sector, fuel, and technology-specific emission factors to quantify emissions occurring directly within that sector. Emissions resulting from energy consumption that are not directly emitted at the point of final energy consumption, were accounted for under the energy supply module. In this analysis, the energy supply sectors included electricity generation and charcoal production. The analysis includes only air pollutants emitted within the Cambodia's national borders (see Section 2.4 for description of the source of non-Cambodia emissions to estimate total $PM_{2.5}$ exposure and health impacts).

In the Residential sector, the total consumption of fuels and electricity was calculated by multiplying the average fuel/electricity consumption per household (energy intensity) by the total number of households. The total consumption of different fuels were then multiplied by fuel and pollutant-specific international default emission factors including from EMEP/EEA (2019), to estimate the air pollutant emissions from the Residential sector. These calculations were done separately for three geographic regions, Phnom Penh, Other Urban areas, and Rural areas, due to the differences in energy consumption patterns in these regions. The total number of households in each region, and the percentage of households using different fuels and with access to electricity in each year were taken from the Cambodia Socio-Economic Survey from 2010 to 2017 (National Institute of Statistics, 2018) (Table 4). For all regions, the energy intensity (fuel/electricity consumption per household using a particular fuel/electricity) for

Table 1
Summary of data sources used to estimate emissions for each source sector.

Source Sector	Activity Data	Source of Data
1A1a Public Electricity and Heat Production	Electricity Transmission and Distribution Losses Percentage of electricity generated using different fuels and technologies (Coal, Heavy Fuel Oil, Diesel, Hydro, Biomass, Wind and Solar) Percentage efficiency of electricity generation using different fuels and technologies	Electricty Authority of Cambodia, 2019
1A1c Manufacture of Solid Fuels (charcoal production)	Efficiency of charcoal kilns	National Energy Statistics 2016 (Ministry of Mines and Energy of Cambodia, 2016)
1A2 Manufacturing Industries and Construction	Fuel Consumption in Industrial sector disaggregated by fuel	National Energy Statistics 2016 (Ministry of Mines and Energy of Cambodia, 2016)
1A3a Civil aviation	Number of passenger-km per year taken by aviation (Domestic and International) Fuel consumption per passenger-km (Landing-take-off cycle only)	Asian Development Bank Transport Databank (Zhang and Emmerson, 2016)
1A3b Road transportation	Number of passenger-km taken by road transport Percentage of road transport passenger-km taken by cars, buses, motorcycles, and non-motorised Percentage of vehicles of each type using Gasoline, Diesel, CNG and Electric fuels Percentage of vehicles meeting different vehicle emission standards (Euro standards)	Department of Land Transportation data on number of vehicles registered Asian Development Bank Transport Databank (Zhang and Emmerson, 2016)
1A3c Railways	Number of passenger-km per year taken by rail Fuel consumption per rail passenger-km	Asian Development Bank Transport Databank (Zhang and Emmerson, 2016)
1A3d Water-borne navigation	Number of passenger-km per year taken by shipping (Domestic and International) Fuel consumption per passenger-km	Asian Development Bank Transport Databank (Zhang and Emmerson, 2016)
1A4a Commercial/ Institutional	Fuel Consumption in commercial and public services sector disaggregated by fuel	National Energy Statistics 2016 (Ministry of Mines and Energy of Cambodia, 2016)
1A4b Residential	Total Number of households, disaggregated by Phnom Penh, Other Urban and Rural areas Percentage of household using Wood, Charcoal, LPG, Kerosene and Electricity in each region Energy consumption per household in each region for each fuel/electricity	Cambodia Socio-Economic Surveys (National Institute of Statistics, 2018) Fast Track Carbon (2014)
1A4c Agriculture, Forestry, Fishing	Fuel Consumption in agriculture sector disaggregated by fuel	National Energy Statistics 2016 (Ministry of Mines and Energy of Cambodia, 2016)
2A Mineral Industry	Cement Production (tonnes per year) Construction and	Ministry of Land Management Urban Planning and Construction

(continued on next page)

Table 1 (*continued*)

Source Sector	Activity Data	Source of Data
	Demolition (Area constructed per year)	(MLMUPC) Data on Construction Area by region
2H Pulp and Paper, Food and Beverage Industry	Paper Production (tonnes per year)	
3B Livestock	Number of Animals	FAO (2022)
3F Field Burning of Agricultural Residues	Crop Area (hectares) for Rice, Maize and Sugarcane	FAO (2022)
	Fraction of crop area burned	
	Mass of crop residue available for combustion	
	Fraction of crop residue available burned	
5C Waste Incineration	Municipal Solid Waste (Phnom Penh and rest of Cambodia modelled separately)	Ministry of Environment of Cambodia (2017)
	Per Capita waste generation rates	
	Waste collection rates	
	Fraction of waste combustible	
	Fraction waste recycled	
	Fraction of waste burned	
	Medical Waste	
	Tonnes of medical waste incinerated	

households using wood and charcoal were set to 4.87 kg wood day^{-1}, and 2.023 kg charcoal day^{-1}, respectively, based on a recent survey of Cambodian households cooking using biomass (Fast Track Carbon, 2014). For LPG, Kerosene and electricity energy intensities, the total consumption of each fuel in Cambodia's national energy balance was divided by the total number of households consuming these fuels to derive a nationally averaged energy intensities (Average, 2010–2017 energy intensities: LPG: 0.445 GJ household^{-1} yr^{-1}, Kerosene: 0.244 GJ household^{-1} yr^{-1}, Electricity: 5.521 household^{-1} yr^{-1}) that were applied to all households in three geographic regions (Ministry of Mines and Energy of Cambodia, 2016).

In the baseline scenario, the number of households in Cambodia were projected to increase with population, at an average rate of 1.4% yr^{-1} between 2016 and 2030, using the United Nations Population Division World Population Prospects 2019 Update Medium Variant (UN DESA, 2019). The division of households between Phnom Penh, Other Urban and Rural regions were kept constant after 2017, consistent with small variation in the proportion of households in each region historically between 2010 and 2017 (National Institute of Statistics, 2018). The energy intensities and number of households using different fuels were also kept constant in each region in the baseline scenario.

In the Industry, Commercial and Public Services, and Agriculture, Forestry and Fishing energy demand sectors, there was insufficient data to disaggregate energy consumption into sub-sectors, or activities. Therefore, for historical years, the total consumption of fuels in each sector was taken from Cambodia's national energy balance (Ministry of Mines and Energy of Cambodia, 2016), and multiplied by fuel and sector-specific international default emission factors to quantify historical air pollutant emissions from each sector. The fuels consumed in each sector between 2010 and 2015 are shown in Table 5. For the baseline scenario, fuel consumption in each sector was projected based on the projected Value Added from the industry, services and agriculture sector, respectively, accounting for the impact of COVID-19 on Cambodia's economy, and the expected economic recovery (Table 2).

In the Transport sector, emissions were estimated for rail, domestic and international aviation (landing and take-offs occurring within Cambodia), domestic and international shipping and road transport. All types of transport were first disaggregated between passenger and freight transport, using the number of passenger-km, and tonnes-km as the activity variables to estimate transport demand. For passenger and freight shipping, aviation and rail, the total number of passenger-km and tonnes-km, respectively, were extracted from the Asia Development Bank Transport Databank (Zhang and Emmerson, 2016), in the absence of country-specific data. The number of passenger and tonnes-km for these transport modes were disaggregated into the proportion that used different types of fuels (diesel and electricity for rail, gasoline, diesel and fuel oil for shipping, and jet kerosene for aviation) and then multiplied by energy intensities for the fuels used (MJ fuel passenger/tonne-km^{-1}). The total energy consumption for each transport mode were then multiplied by default fuel-specific international emission factors for each pollutant (EMEP/EEA, 2019).

For road transport, the number of passenger-km and tonnes-km taken by road vehicles was calculated based on country-specific data on the number of vehicles of different types provided by the Department of Land Transportation. The number of vehicles sold (i.e. new vehicles introduced into the fleet) between 1990 and 2020 were used as inputs to a stock-turnover model to estimate the total number of active vehicles for four vehicle categories, motorcycles, cars, buses, and heavy-duty vehicles. The stock-turnover model assumed that the retirement rate of vehicles in Cambodia were the same as those measured previously in Thailand, in the absence of country-specific retirement rates. The Department of Land transport data included the total number of heavy-duty vehicles only. Therefore, to construct the stock-turnover model, 10% of this category were assumed to be buses, and contribute to meeting passenger transport demand, with the remaining 90% assigned as heavy-duty vehicles (e.g. trucks) to meet freight transport demand.

The estimated number of vehicles in the vehicle fleet of each type in a particular year were multiplied by default values for the average distance travelled (km y^{-1}), and load factor (passengers or tonnes freight vehicle^{-1}) from the ADB transport databank to convert the number of vehicles to the number of passenger-km and tonnes-km for each vehicle type (Zhang and Emmerson, 2016). The key statistics used to estimate the number of passenger-km and tonnes-km in the road transport sector are shown in Table 6. The passenger-km and tonnes-km for each vehicle type were then disaggregated by fuel, and Euro vehicle emission standards. The percentage of vehicles meeting different Euro standards were not available from measured vehicle emission levels, and were instead estimated based on the year in which vehicles entered the vehicle fleet in Cambodia. For vehicles older than 10 years, they were assumed to not meet any Euro standards. Those vehicles between 5 and 10 years old were assumed to meet Euro 3 standards, and those less than 5 years old were assumed to meet Euro 4 standards. Cambodia does not yet use fuel

Table 2
Key socioeconomic parameters for Cambodia for historic (2010–2015) and baseline projection (2016–2030).

	2010	2011	2012	2013	2014	2015	2020	2025	2030
Population (Million people)	14.312	14.554	14.796	15.038	15.280	15.521	16.719	17.806	18.781
GDP (billion Riel)	30,403	32,553	34,933	37,503	40,182	42,981	55,527	72,893	99,869
Agriculture Value Added (billion Riel)	8311	8567	8936	9076	9101	9120	9538	10,392	11,357
Industry Value Added (billion Riel)	8088	9259	10,124	11,210	12,341	13,760	20,280	29,108	44,715
Services GDP (billion Riel)	11,857	12,449	13,458	14,626	15,903	17,027	21,402	27,722	37,139
Construction GDP (billion Riel)	1485	1603	1895	2154	2614	3089	5909	8970	15,454

Table 3
Assumptions about socioeconomic development in Cambodia that informed the development of the baseline scenario.

Source Sector	Variable used for baseline projections	Value
1A1a Public Electricity and Heat Production	Projection of electricity demand (from electricity consuming sectors)	Derived from energy demand modelling in LEAP
1A1c Manufacture of Solid Fuels (charcoal production)	Future demand for charcoal	Determined from charcoal consumption in energy demand sector (i.e. 1A4b Residential)
1A2 Manufacturing Industries and Construction	Value added GDP for industry	Average 14% per year increase between 2015 (13,760 billion Riels) and 2030 (44,715 billion Riels) (Table 2)
1A3a Civil aviation	Number of passenger-km taken by aviation	GDP growth rate projections (Table 2)
1A3b Road transportation	Number of passenger-km taken by road	GDP growth rate projections (Table 2)
1A3c Railways	Number of passenger-km taken by rail	GDP growth rate projections (Table 2)
1A3d Water-borne navigation	Number of passenger-km taken by shipping	GDP growth rate projections (Table 2)
1A4a Commercial/ Institutional	Fuel consumption in commercial/institution sector	Services value Added: Average 7.87% per year increase between 2015 (17,027 billion Riels) and 2030 (37,139 billion Riels) (Table 2)
1A4b Residential	Number of households	Population growth rate (1.4% per year) (Table 2)
1A4c Agriculture, Forestry, Fishing	Fuel consumption for agriculture	Agriculture Value Added: Average 1.55% per year increase between 2015 (9120 billion Riels) and 2030 (11,357 billion Riels) (Table 2)
2A Mineral Industry	Cement Production (tonnes per year) Construction and Demolition (Area constructed per year)	Industry Value Added: Average 14% per year increase between 2015 (13,760 billion Riels) and 2030 (44,715 billion Riels) (Table 2) Construction Value Added: Average 27% per year increase between 2015 (3089 billion Riels) and 2030 (15,454 billion Riels) (Table 2)
2H Pulp and Paper, Food and Beverage Industry	Paper Production (tonnes per year)	Industry Value Added: Average 14% per year increase between 2015 (13,760 billion Riels) and 2030 (44,715 billion Riels) (Table 2)
3B Livestock	Number of Animals	Animal specific growth rates
3F Field Burning of Agricultural Residues	Crop Area (hectares) for Rice, Maize and Sugarcane	Agriculture Value Added: Average 1.55% per year increase between 2015 (9120 billion Riels) and 2030 (11,357 billion Riels) (Table 2)
5C Waste Incineration	Municipal Solid Waste Generated	Population growth rate (1.4% per year) (Table 2)

with sufficiently low sulphur content for Euro 5 and Euro 6 vehicle standards to be met by the vehicle fleet, and hence no vehicles were assumed to be meeting these standards. The number of passenger-km and tonnes-km for each road transport vehicle type, fuel and Euro standard, were then multiplied by default energy intensities (quantity of fuel per passenger/tonne-km travelled), and emission factors for each pollutant (EMEP/EEA, 2019).

For the baseline scenario, in the shipping, aviation and rail sectors, the number of passenger-km and tonnes-km were projected to increase at the same rate as GDP in Cambodia. For the road transport sector, for passenger demand, the number of passenger-km were projected reflecting population and income projections. The historic elasticity between total per capita passenger-km and GDP per capita (which ranged between 1.010 and 1.065 between 2010 and 2019, average: 1.042) was calculated, and the average elasticity used to project total per capita passenger-km between 2020 and 2030 based on projected GDP per capita in the future (Table 2). The total number of passenger-km was calculated by multiplying future per capita passenger-km by the future population. This approach does not account for the saturation of passenger-km at high income levels, the projected per capita passenger-km in 2030 (14,425 km $person^{-1}$), is lower than saturation rates in high-income countries (Ecola et al., 2014). For freight demand, the elasticity between the total number of tonnes-km and total GDP was calculated for 2010–2019 (varied between 0.956 and 1.069, average: 1.030), and was used to project total tonnes-km based on projected GDP growth rates. The share of road transport vehicle types, fuels and Euro standards were kept constant in the baseline scenario.

In the transformation sector, the requirements for electricity generation were based on the domestic demand for electricity (modelled as described above for the energy demand sectors), and the losses from electricity transmission and distribution from Cambodia's national energy balance (Ministry of Mines and Energy of Cambodia, 2016) (Table 7). Power stations generating electricity to meet demand were aggregated by fuel type, i.e. the electricity generated from coal, heavy fuel oil, diesel, hydro, biomass and wind and solar power plants. The quantity of fuel consumed at each type of power plant was calculated based on the percentage share of electricity generated using each power station, and the efficiency of generating electricity from a particular power station. Both values were derived from Cambodia's National Energy Balance (Table 7) and were assumed to stay constant in the baseline scenario (Ministry of Mines and Energy of Cambodia, 2016). The total fuel consumption in each type of power station was multiplied by fuel-specific default emission factors to estimate emissions from each pollutant (EMEP/EEA, 2019).

Charcoal production emissions were also included in the energy transformation sector analysis. The annual production of charcoal was assumed to be equal to the domestic consumption of charcoal, calculated in the residential sector modelling described above. The wood consumed to produce this charcoal was estimated by dividing the charcoal produced by the efficiency of the charcoal production kilns, which were assumed to be 11.4% efficient, based on Cambodia's National Energy Balance (Ministry of Mines and Energy of Cambodia, 2016). Baseline projections assumed no improvement in charcoal kiln efficiency, and the quantity of charcoal production changed in future years in response to changes in residential sector consumption of charcoal for cooking.

2.2.2. Industrial Processes and other Product Use (IPPU)

The emissions from the IPPU sector reflected non-fuel combustion process emissions from the cement, paper and construction industries. For each of the IPPU sub-sectors the EMEP/EEA (2019) Tier 1 methods were used to estimate historic and future emissions. For cement production, and paper production, the total product production (Table 8) were multiplied by default sub-sector and pollutant-specific emission factors. For the baseline scenario, the production of these products were projected to increase at the same rate as the increase in Value Added GDP from the industrial sector (Table 2).

The third sub-sector included was construction. The activity data for construction emissions was the number of squares metres of construction area for non-residential, residential, industrial and commercial sectors (EMEP/EEA, 2019), and were provided by the Ministry of Land Management Urban Planning and Construction (MLMUPC) (Table 8). Emissions were estimated for primary $PM_{2.5}$ and PM_{10} and were calculated by multiplying the affected area by the building duration (EMEP/EEA (2019) default values), and assuming no control measures were put in place to reduce emissions. In the baseline scenario, the area

Table 4
Number of households and percentage of households using fuels and technologies in three geographic regions extracted from Cambodia Socio-Economic Survey reports.

	2010	2011	2012	2013	2014	2015	2016	2017
Number of households								
Phnom Penh	276	302	329	363	369	389	381	374
Other Urban	298	347	398	331	366	360	364	369
Rural	2344	2351	2355	2468	2526	2558	2613	2666
Fuels Used (% households)								
Phnom Penh								
Wood	11.1	13.8	16.6	8.5	9.3	15.4	11.5	8.4
Charcoal	11.8	13.8	15.8	16.2	8.3	6.0	3.5	3.3
LPG	74.7	70.9	67.2	74.9	79.5	77.8	80.7	84.9
Kerosene	0.7	0.5	0.3	0.3	0.3	0.3	0.3	0.3
Electricity	99.0	98.8	98.6	100.0	99.3	99.2	99.7	99.6
Other Urban								
Wood	43.0	44.6	46.2	38.4	43.2	42.1	37.3	35.6
Charcoal	31.3	27.3	23.4	24.2	20.8	22.3	26.0	17.2
LPG	23.1	25.5	28.0	33.1	33.7	32.3	33.3	45.6
Kerosene	12.4	8.2	4.0	2.2	2.3	1.5	1.2	0.4
Electricity	78.1	82.5	87.0	94.3	91.7	94.1	93.0	95.9
Rural								
Wood	91.7	91.6	91.5	90.9	88.9	87.3	85.0	79.1
Charcoal	5.9	5.3	4.8	5.0	6.3	6.4	5.4	6.6
LPG	2.1	2.5	2.9	3.3	3.9	5.2	8.3	13.0
Kerosene	34.8	29.3	23.8	15.5	9.1	4.0	2.8	1.6
Electricity	18.8	22.8	26.8	37.9	47.3	57.9	69.9	72.4

Table 5
Final energy consumption in industry, commercial and public services and agriculture sectors in Cambodia between 2010 and 2015 disaggregated by fuel (units: Thousand tonnes of oil equivalent).

Fuel	2010	2011	2012	2013	2014	2015
Industry						
Coal	5.02	5.60	5.31	6.38	8.02	5.02
LPG	–	0.05	0.92	–	0.92	–
Diesel	65.98	64.34	68.10	67.43	72.93	65.98
Heavy Fuel Oil	123.99	120.27	102.64	89.31	58.68	123.99
Other Petroleum Products	2.95	5.60	3.53	3.62	4.44	2.95
Wood	244.01	236.81	234.40	251.55	257.05	244.01
Electricity	41.06	50.33	68.10	64.72	80.95	41.06
Commercial and Public Services						
LPG	30.59	25.27	14.63	14.63	9.31	30.59
Kerosene	14.63	6.65	2.66	1.33	–	14.63
Heavy Fuel Oil	10.64	21.28	19.95	11.97	6.65	10.64
Electricity	77.14	79.80	95.76	105.07	117.04	77.14
Agriculture, Forestry and Fishing						
Diesel	32.0	38.0	44.0	42.0	50.0	38.0

constructed upon were estimated to increase at the same rate as Value Added GDP for the construction sector (Table 2).

2.2.3. Agriculture

For agriculture, the air pollutant emissions covered are those from manure management (NH_3), and crop residue burning (multiple air pollutants). For manure management, the total number of each livestock animal (FAO, 2022, Table 9) were multiplied by default emission factors for NH_3 from EMEP/EEA (2019). For crop residue burning, the annual area of crop cultivated (FAO, 2022, Table 9) was multiplied by the tonnes of residue available for burning per hectare, the fraction of the residue burned in fields, and default emission factors for crop burning from EMEP/EEA (2019). For the baseline scenario, in the absence of specific projections for crop production and livestock, the number of animals and crop production were projected to increase at the same rate as agricultural GDP (Table 2).

2.2.4. Waste

In the waste sector, emissions from the open burning of municipal solid waste, and from incineration of medical waste were estimated. For open burning of municipal solid waste, emissions were estimated separately for Phnom Penh, and the rest of Cambodia, due to differences in waste generation and collection rates between the capital and other areas (Ministry of Environment of Cambodia, 2017). The total waste generated in each region was calculated by multiplying the population in each region (assuming that 18% of the national population live in Phnom Penh, and 82% in the rest of Cambodia) by region-specific waste generation rates (Table 10) taken from Ministry of Environment of Cambodia (2017). The waste collected and sent to landfills or recycled, and uncollected was then estimated using the statistics reported in Ministry of Environment of Cambodia (2017). For waste that was uncollected or sent to landfills, the quantity of waste was multiplied by the fraction of waste that is combustible, the fraction of waste that is actually burned, and by pollutant-specific emission factors from EMEP/EEA (2019) to estimate the emissions from waste burning. The composition of waste (to estimate the combustible fraction) was taken from Ministry of Environment of Cambodia (2017). However, there is not country-specific information on the fraction of uncollected, and waste sent to landfills that is actually burned, and therefore the IPCC (2006) default factor of 0.6 was used in the absence of country-specific data, consistent with global open waste burning emission assessments (Wiedinmyer et al., 2014). For medical waste incineration, the tonnes of medical waste incinerated from Ministry of Environment of Cambodia (2017) was used as the activity variable, and multiplied by default emissions factors (EMEP/EEA, 2019). For the baseline scenario, the increase in waste generated was based on the growth in population, with all other variables remaining constant.

2.3. Mitigation scenarios

The first set of mitigation measures included in the assessment were those included in the Prime Minister's Circular, published in 2020 (The Royal Government of Cambodia, 2020). These measures were included as they are the most recent announcement of the mitigation measures the Royal Government of Cambodia supports to improve air quality. Additional mitigation measures in key sources not included in the Circular were also evaluated. In total, 15 mitigation measures were modelled and included in the mitigation assessment. Each mitigation measure was defined with a target and timeline for implementation. The mitigation measures included in the assessment are summarised in Table 11. In addition to the Circular, mitigation measures were

Table 6
Key characteristics of transport sectors between 2010 and 2015.

	2010	2011	2012	2013	2014	2015
Shipping Passenger transport demand (billion passenger-km)	1.77	1.77	1.77	1.77	1.77	1.77
Shipping passenger gasoline energy intensity (MJ passenger-km^{-1})	1.63	1.63	1.63	1.63	1.63	1.63
Shipping Freight transport demand (billion tonnes-km)	0.138	0.138	0.138	0.138	0.138	0.138
Shipping freight diesel energy intensity (MJ tonne-km^{-1})	0.112	0.112	0.112	0.112	0.112	0.112
Number of motorcycles in vehicle fleet (vehicles)	1,096,917	1,264,077	1,435,747	1,607,080	1,823,968	2,065,500
Motorcycle average distance travelled (km vehicle^{-1} y^{-1})	7200					
Motorcycle load factor (passenger vehicle^{-1})	1.5					
Motorcycle Fuel	Gasoline: 100%					
Number of cars in vehicle fleet (vehicles)	160,455	180,658	201,040	220,128	241,601	273,888
Cars average distance travelled (km vehicle^{-1} y^{-1})	15,000					
Car load factor (passenger vehicle^{-1})	4					
Cars Fuel (% fuel)	Gasoline: 80% Diesel:16% CNG: 4%					
Number of buses in vehicle fleet (vehicles)	9157	10,064	11,323	12,602	13,967	15,725
Bus average distance travelled (km vehicle^{-1} y^{-1})	40,000					
Bus load factor (passenger vehicle^{-1})	40					
Bus Fuels (% fuel)	Gasoline: 4% Diesel:79% CNG: 17%					
Number of heavy-duty vehicles in vehicle fleet (vehicles)	79,746	87,645	98,613	109,745	121,638	136,948
Heavy Duty Vehicle average distance travelled (km vehicle^{-1} y^{-1})	49,000					
Heavy Duty Vehicle load factor (tonnes vehicle^{-1})	9					
Heavy Duty Vehicle Fuel	Gasoline: 3% Diesel:86% LPG: 11%					

Table 7
Key variables used to model electricity generation and associated fuel consumption.

	2010	2011	2012	2013	2014	2015
Transmission and Distribution Losses (% electricity generated)	28.60	27.92	18.27	28.07	23.42	23.42
Process Share (% electricity generated)						
Coal	3.7	5.2	2.8	10.2	29.0	47.8
Heavy Fuel Oil	89.8	86.8	56.5	28.7	8.9	3.2
Diesel	1.4	1.3	0.6	0.0	0.0	–
Hydro	3.6	5.2	39.2	60.7	61.8	48.4
Biomass	1.5	1.6	0.9	0.4	0.4	0.6
Percent efficiency						
Coal	16.19	19.99	11.09	31.54	26.60	36.82
Heavy Fuel Oil	38.62	36.39	36.44	37.63	36.85	28.19
Diesel	17.86	16.35	7.87	7.87	7.87	7.87
Hydro	100	100	100	100	100	100
Biomass	36.54	24.33	19.78	18.20	13.71	12.90

identified from other plans that include actions that target emission sources, such as Cambodia's Climate Change Strategic Plan and Nationally Determined Contribution (Kingdom of Cambodia, 2020; National Climate Change Committee, 2013). In addition, for those sectors which are large air pollution emission sources (e.g. charcoal production and freight transport), expert judgement was used to identify mitigation measures in these sectors that were not included in existing plans in Cambodia.

The air pollutant emission reductions from implementing the individual mitigation measures were evaluated, and scenarios that reflected the implementation of all measures in i) the Circular only, and ii) the Clean Air Plan (including the measures in the Circular) were also modelled. The combined scenarios estimate the extent to which implementing the full programme of actions included in the Clean Air Plan could improve air quality, and also accounting for interactions between different mitigation actions.

2.4. Estimating $PM_{2.5}$ exposure and health burden

To quantify the health benefits that could result from the implementation of the mitigation measures included in Cambodia's Clean Air Plan, an air pollution health impact assessment was undertaken using the methods described in Kuylenstierna et al. (2020). The health endpoint used is premature mortality attributable to $PM_{2.5}$ exposure for children (less than 5 years) and adults (>30 years) in 5-year age groups (30–34, 35–39 … 75-79, >80 years) from 5 disease categories (children: acute lower respiratory infection; adults: chronic obstructive pulmonary disease, ischemic heart disease, cerebrovascular disease and lung cancer). The metric used to quantify long-term exposure to ambient air pollution is the national population-weighted annual average ambient $PM_{2.5}$ concentration, i.e. the average exposure across all Cambodians, averaged across the year (REVIHAAP, 2013).

To quantify premature mortality attributable to ambient $PM_{2.5}$ exposure for each population group and each disease category, national population-weighted annual average $PM_{2.5}$ concentrations were combined with 'integrated exposure response' (IER) functions that have previously been extensively used for quantifying air pollution health burdens (Burnett et al., 2014; Cohen et al., 2017). The IER functions (Equation (1)) quantify the relative risk (RR) for mortality from specific

Table 8
Variables used to estimate emissions from the IPPU sector in Cambodia.

	2010	2011	2012	2013	2014	2015
Cement Production (tonnes yr^{-1})						1,389,880
Paper Production (tonnes yr^{-1})					66,762	76,576
Construction non-residential (thousand m^2)	184.64	55.31	71.05	92.84	48.94	48.94
Construction residential (thousand m^2)	1469.66	2051.14	2682.43	2075.45	3165.69	3165.69
Construction industrial (thousand m^2)	614.80	1323.73	2008.48	1479.73	1725.90	1725.90
Construction commercial (thousand m^2)	144.91	334.41	1166.47	3203.10	977.35	977.35

Table 9
Variables used to estimate emissions from agriculture in Cambodia.

	2010	2011	2012	2013	2014	2015
Number of animals						
Cattle	3,484,601	3,406,972	3,418,934	3,430,895	3,053,481	2,903,420
Buffalo	702,074	689,829	654,472	619,114	541,827	506,166
Pigs	2,057,431	2,099,332	2,268,016	2,436,699	2,360,823	2,357,839
Sheep	818	673	528	383	238	378
Goats	14,264	15,262	16,260	17,258	18,256	23,321
Horses	13,210	12,198	11,186	10,173	9161	7637
Poultry	20,834,295	22,036,755	24,676,585	27,316,415	25,630,027	26,688,675
Crop Area (hectare)						
Rice	2,777,323	2,766,617	2,980,297	2,968,967	3,028,836	3,025,630
Maize	214,000	174,257	215,442	207,788	120,016	88,591
Sugarcane	17,072	22,069	27,859	30,665	25,503	27,316
Tonnes residue per hectare available for burning						
Rice	0.510					
Maize	12.5					
Sugarcane	8.125					

Table 10
Variables used to estimate emissions from waste burning in Cambodia.

	Value
Waste Generation Rate (kg/person/day)	
Phnom Penh	1
Rest of Cambodia	0.55
Percentage waste uncollected	
Phnom Penh	16.7%
Rest of Cambodia	49.0%
Percentage Waste Recycled	
Phnom Penh	5%
Rest of Cambodia	8.9%
Percentage Waste sent to landfill	
Phnom Penh	78.3%
Rest of Cambodia	42.1%
Fraction of waste that is combustible	95%
Fraction burned	60%
Medical waste incinerated (tonnes per year)	3347 (2015 estimate)

diseases for $PM_{2.5}$ exposures up to very high levels (up to 10,000 μg m^{-3}), by integrating RRs derived from epidemiological studies between cause-specific mortality and $PM_{2.5}$ exposure from ambient air pollution, household air pollution, second hand smoke, and active smoking.

$$RR_{IER} = 1 + \alpha\left(1 - e^{-\gamma\left(z - z_{cf}\right)^{\delta}}\right) \quad \text{Eq. 1}$$

Where z_{cf} is the $PM_{2.5}$ low concentration cut-off, z is the $PM_{2.5}$ concentration that a population is exposed to, and α, δ, and γ are IER-specific parameters (Burnett et al., 2014; Cohen et al., 2017). The RR derived from the IER function for a particular disease and age group, is then used in combination with the baseline mortality rate for that disease for the population in the target country, and the exposed population in the age category in the target country to estimate the number of premature deaths attributable to ambient $PM_{2.5}$ exposure from the particular disease in that age group (Equation (2)).

$$\Delta \text{Mort} = y_0\left(\frac{RR_{IER} - 1}{RR_{IER}}\right)Pop \quad \text{Eq. 2}$$

Here y_0 is the baseline mortality rate for each disease category, and Pop is the exposed population for each child or adult age category. Baseline mortality rates for each disease category were taken from Abbafati et al. (2020).

Following methods outlined in Kuylenstierna et al. (2020), population-weighted annual average $PM_{2.5}$ concentrations were estimated by combining the emissions estimated for each $PM_{2.5}$ and $PM_{2.5}$-precursor pollutants described in Sections 2.2 and 2.3 with outputs from source-receptor calculations performed with the adjoint of the atmospheric chemistry transport model GEOS-Chem (Bey et al., 2001; Henze et al., 2007; Kuylenstierna et al., 2020). National total emissions of primary $PM_{2.5}$ (black carbon, organic carbon and other primary PM emissions), and secondary inorganic $PM_{2.5}$ precursors (NO_x, SO_2 and NH_3) for Cambodia were spatially distributed into 2° x 2.5° grids covering the country to match the scale of the GEOS-Chem adjoint model results (see below). The proportion of national total emissions of each pollutant assigned to the 2° x 2.5° grids covering the country was based on the spatial distribution of emissions across Cambodia in an existing gridded emission dataset, the IIASA GAINS ECLIPSE emissions dataset (Stohl et al., 2015). ECLIPSE estimates emissions of SLCPs and air pollutants for historical and future projections in 0.5° grids globally. For those grids that cover the target country, the ECLIPSE emissions were apportioned between Cambodia and neighbouring countries based on population distribution (using the Gridded Population of the World v3 dataset (CIESIN, 2005)). This ensured that the LEAP-derived emissions only replace the emissions associated with the target country. Air pollutant emitted outside of Cambodia can also be transported and impact $PM_{2.5}$ concentrations in Cambodia. Therefore, air pollutant emissions for the rest of the world were represented by the gridded ECLIPSE emissions outside of the target country (Stohl et al., 2015). The ECLIPSE 'current legislation' scenario was used to represent future air pollutant emissions outside of Cambodia for both baseline and mitigation scenarios.

To translate gridded emissions to population-weighted annual average $PM_{2.5}$ concentrations, accounting for transport and chemical processing in the atmosphere, the gridded emissions are then combined with output from the adjoint of the GEOS-Chem global atmospheric chemistry transport model (Henze et al., 2007). The GEOS-Chem adjoint model quantifies the relationship between emissions of a particular pollutant that contributes directly to $PM_{2.5}$ (BC, OC or other PM), or is a precursor to $PM_{2.5}$ (NO_x, SO_2 and NH_3) in any location, and the associated change in population-weighted $PM_{2.5}$ in the target country. GEOS-Chem simulates the formation and fate of pollutants globally at a grid resolution of 2° × 2.5°, with 47 vertical levels. Emissions of aerosols and aerosol precursors include both natural (i.e., ocean, volcanic, lightning, soil, biomass burning, biogenic and dust) and anthropogenic (transportation, energy, residential, agricultural, etc.) sources. The adjoint of the GEOS-Chem model calculates the sensitivity of a particular model response metric (in this case population-weighted annual average surface $PM_{2.5}$ concentration across the target country) with respect to an emission perturbation in any of the global model 2° × 2.5° grid cells (Henze et al., 2007), accounting for all of the mechanisms related to aerosol formation and fate. These sensitivities are output from the GEOS-Chem adjoint as gridded 'coefficients', which are then multiplied by emission estimates in IBC to estimate the change in population-weighted annual average $PM_{2.5}$ concentrations in Cambodia for each year and emission scenario.

Table 11
Summary of mitigation measures evaluated for GHG emission reduction potential from plans and strategies in Cambodia.

No.	Sector	Mitigation Measure	Source	Goal	Time line
1	Construction	Administration of Construction Sites to reduce dust and particulate matter emissions	Circular on Air Pollution	50% of all construction projects implement air pollution reduction measurement on Administration of Construction Sites	1.2030
2	Transport	Improve fuel quality and promote the implementation of sulphur content standards	Circular on Air Pollution	1. Sulphur level to meet Euro III levels 2. Sulphur level to meeting Euro IV levels 3. Sulphur level to meet Euro V levels	1.2020 2.2021 3.2024
3	Transport	Implement Euro vehicle emission standards on imported tour buses	Circular on Air Pollution	1. Imported tour buses to meet Euro IV 2. Imported tour buses to meet Euro V	1.2022 2.2027
4	Transport	Implement Euro vehicle emission standards on all motorcycles sold	Circular on Air Pollution	1. All imported motorcycles to meet Euro III	2023
5	Transport	Developing or improving public transport strategy focusing on air pollution reduction	Circular on Air Pollution	Assume 10% shift in journeys from private cars to public transport	2030
6	Transport	Implement Euro vehicle emission standards on all passenger cars sold	Circular on Air Pollution	All old or new import cars comply with EU IV emission standard	2022 Euro IV
7	Industry	Promoted the technical installation of smoke and dust filters in the production site in order to reduce the release of toxic gases into the air through the implementation of new technologies including	Circular on Air Pollution	80% of all industries implement air pollution reduction technologies at production sites, with effectiveness of technologies, assume a 50% reduction in industrial emissions	2030
8	Agriculture/ Waste	Reduce open burning of agricultural and municipal solid waste	Circular on Air Pollution	50% reduction of illegal opened waste burning across the country including agricultural residues and municipal solid waste	2030
9	Residential	Promote and install cooking using biogas in rural areas	Cambodia Climate Change Strategic Plan 2014–2023	60% of residential in rural switch from using biomass to biogas	2030
10	Energy Efficiency	Improve energy efficiency in residential, commercial and industrial sectors through Minimum Energy Performance Standards, public awareness campaigns, building codes, and more efficient technologies in industry.	Cambodia's Nationally Determined Contribution	Energy efficiency in residential sector improves by 31.7% Energy efficiency in services sector improves by 41.7% Energy efficiency in industry sector improves by 2.3%	2030
11	Renewable electricity generation	25% of electricity from renewable sources by 2030	Cambodia's Nationally Determined Contribution	25% of the renewable energy in the energy mix (solar, wind, hydro, biomass) by 2030	2030
12	Charcoal Making	Improve efficiency of charcoal production	Additional mitigation measure not included in current plans	Assume charcoal kiln efficiency increases from 11% to best available 30% efficiency	2030
13	Freight Transport	Implement Euro 4 standards across Freight transport system	Additional mitigation measure not included in current plans	Assume all new heavy duty vehicles meet Euro 4 standards from 2022	2022
14	Passenger Transport	Implement Euro 4 standards for all buses	Additional mitigation measure not included in current plans	Assume all new buses meet Euro 4 standards from 2022	2022

Adjoint coefficients were produced for each pollutant that contributes to population-weighted annual average $PM_{2.5}$ concentrations, namely, BC, OC, NO_x, SO_2, NH_3 and other PM (in this case, predominantly mineral dust), reflecting their different reactivity and formation pathways in the atmosphere. The coefficients applied were derived using meteorological parameters for 2010 for all years, to assess the impact only of changes in air pollutant emissions on ambient $PM_{2.5}$ concentrations, as opposed to changes in climate. Emission changes have been shown to be the dominant factor in long-term changes in air pollutant concentrations, and are the focus of this work (Pye et al., 2009). The adjoint coefficients were applied by multiplying, in each grid and for each pollutant, the coefficient by emissions, and summing across all grids to estimate the population-weighted $PM_{2.5}$ concentration across Cambodia for a particular year for a particular scenario. These population-weighted annual average $PM_{2.5}$ concentrations were then used in Equations (1) and (2) to estimate the number of premature deaths attributable to ambient air pollution for each year and emission scenario. Premature mortality attributable to ambient $PM_{2.5}$ exposure was estimated for 2015, and for 2030 for the baseline scenarios and for the scenario that reflect the implementation of all mitigation measures. See Kuylenstierna et al. (2020) for further details.

3. Results

The air pollutant mitigation assessment results include first the magnitude of emissions of air pollutants in Cambodia between 2010 and 2015 and the baseline projection to 2030 (Section 3.1). The reduction in air pollutant emissions that could be achieved from implementation of the mitigation measures included in Cambodia's Clean Air Plan are outlined in Section 3.2. Finally, the estimated change in $PM_{2.5}$ exposure and health benefits from these reductions in air pollutants is described in Section 3.3.

3.1. Historical air pollutant emissions and baseline projections to 2030

Four particulate matter pollutant metrics were included in the analysis, primary $PM_{2.5}$ and PM_{10}, and BC and OC (Table 12). In 2015, the emissions of these 4 PM pollutants was dominated by the Residential sector, with at least 40% of national total emissions coming from the Residential sector in 2015 (Table 13, Fig. 1). Waste burning was estimated to be the second largest of $PM_{2.5}$, PM_{10} and organic carbon emissions in 2015, contributing between 25 and 30% of national total emissions (Fig. 1, Table 13). Waste burning was a smaller fraction of black carbon emissions (14% in 2015), and the transport sector was the second largest source of black carbon emissions. Charcoal production,

Table 12
National total air pollutant emissions between 2010 and 2015, and for future years in the baseline scenario.

Pollutant	2010	2011	2012	2013	2014	2015	2020	2025	2030	% change 2015–2030
Carbon Dioxide	9161.8	10,370.2	10,061.8	10,120.0	11,796.1	13,608.1	18,444.6	26,438.6	40,150.8	195.1
Carbon Monoxide	978.5	998.6	1038.3	1098.2	1149.9	1234.2	1492.5	1952.9	2725.6	120.8
Non Methane Volatile Organic Compounds	346.4	352.5	369.4	397.5	425.8	462.2	578.9	778.5	1119.2	142.2
Nitrogen Oxides	83.6	90.8	96.8	103.3	114.3	127.0	158.0	221.4	329.0	159.0
Particulates PM10	74.0	76.6	79.7	81.6	81.4	83.9	92.5	107.9	132.4	57.9
Sulphur Dioxide	63.7	75.7	57.8	43.9	33.8	32.9	41.0	52.2	70.0	112.7
Ammonia	138.1	136.8	139.4	141.8	128.6	124.9	114.0	109.9	112.0	−10.3
Particulates PM2pt5	61.4	62.9	64.4	65.6	65.9	68.1	72.9	83.3	98.5	44.6
Black Carbon	7.2	7.4	7.7	7.9	8.1	8.5	9.3	11.4	14.6	72.3
Organic Carbon	28.7	29.2	30.0	30.6	30.6	31.8	34.0	38.6	45.0	41.2

Table 13
Emissions of air pollutants from major sources in 2015 in Cambodia.

	OC	BC	PM2.5	NH3	SO2	PM10	NOx	NMVOC	CO	CO2
Residential	12.7	3.8	29.3	4.0	3.6	36.5	9.9	118.0	372.0	14.9
Transport	2.3	1.9	6.2	0.2	2.4	6.2	90.5	189.5	437.5	8233.4
Industry	1.0	0.6	2.0	0.0	2.7	2.0	3.7	4.1	8.3	402.5
Electricity Generation	0.0	0.0	0.2	0.0	20.8	0.4	10.2	0.1	0.4	4043.9
Charcoal Production	4.2	0.6	8.4	1.2	1.9	8.4	0.6	105.5	311.5	–
Other Energy	0.0	0.1	0.2	0.0	0.3	0.2	1.7	0.1	0.3	226.8
Agriculture	1.7	0.3	2.9	117.4	0.2	3.0	1.2	2.3	32.5	–
Industrial Processes	–	0.0	0.7	–	0.2	4.8	0.1	0.2	0.4	686.6
Waste	9.9	1.2	18.4	2.1	0.9	22.4	9.2	42.5	71.4	–
Total	31.8	8.5	68.1	124.9	32.9	83.9	127.0	462.2	1234.2	13,608.1

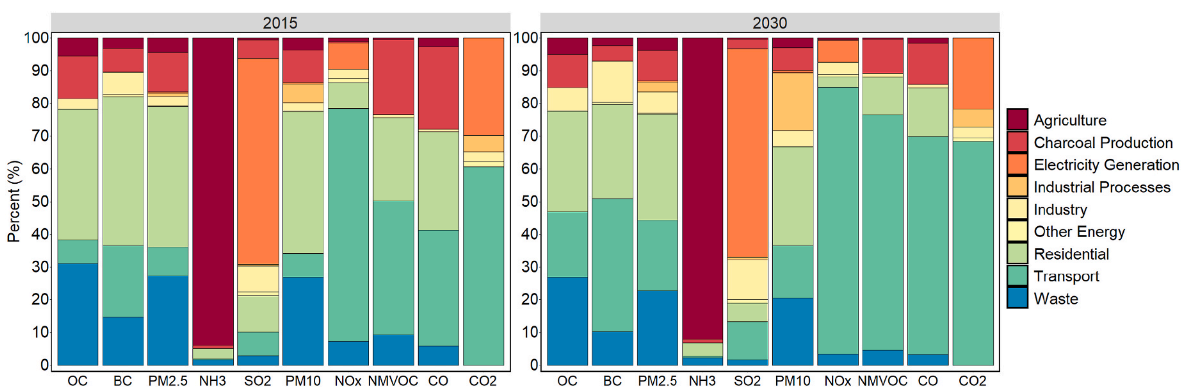

Fig. 1. Contribution of major sources to national total air pollutant emissions in a) 2015 and b) 2030.

agricultural waste burning, and construction made smaller, but not insignificant contributions to the particulate matter pollutant emissions between 2010 and 2015.

For the gaseous air pollutants, the source profile for VOCs, and for CO was similar as for the particulate matter pollutants, but with larger contributions from transport and charcoal production, compared with the residential and waste sectors. Nitrogen oxides emissions were predominantly (71% in 2015) from the transport sector, followed by electricity generation. Sulphur dioxide emissions were mainly emitted from electricity generation. Finally, NH_3 emissions were almost exclusively emitted from agriculture.

The analysis of national total emissions of gaseous and particulate pollutants therefore highlights five key sectors, residential, transport, waste, electricity generation and agriculture, as being those that make the major contributions to air pollutant emissions in Cambodia. This provides an indication of where mitigation efforts need to be focussed to reduce air pollutant emissions that are occurring currently. The transport and electricity generation sectors were estimated to be the two largest sources of CO_2 emissions (Fig. 1). This underlines the opportunity that integrated strategies could be designed to simultaneously improve air quality in Cambodia while at the same time reducing Cambodia's contribution to climate change.

The baseline projection of emissions also indicates that air pollutant emissions could increase substantially in Cambodia to 2030, as a result of socioeconomic growth. For particulate matter pollutants, increases in emissions of between 41% and 60% between 2015 and 2030 were projected (Table 12). The contribution to these emissions in 2030 from the residential sector was estimated to be lower than in 2015, contributing approximately 30% of emissions of $PM_{2.5}$, PM_{10}, BC and OC in 2030. The contribution of the waste sector was also smaller. There were larger relative contributions from the transport and industrial sectors, reflecting the relatively large economic growth rates used to project emissions in these sectors into the future. Baseline projections of gaseous air pollutant emissions were even greater compared with particulate matter pollutants, reflecting the large growth rates in the transport sector, which makes a larger relative contribution to gaseous air pollutants. For example, VOC, CO and NO_x emissions were projected to increase 140%, 120% and 160%, respectively, in large part due to large increase in transport demand (Table 12, Fig. 1).

3.2. Mitigation of air pollutant emissions from Cambodia's First Clean Air Plan

The effectiveness of different mitigation measures in reducing air pollutant emissions up to 2030 were evaluated for mitigation measures individually (Table 14), and for two scenarios that grouped different mitigation measures together (Fig. 2 and Table 14). The first combined scenario reflects the mitigation measures included in the Circular, which have been announced by the Government but for which emission reductions have not been quantified. The second scenario includes all measures included in Cambodia's First Clean Air Plan, including those in the Circular as well as the additional measures included only in the Clean Air Plan, as outlined in Table 11.

These two scenarios show that the implementation of the Circular, and Clean Air Plan, would be effective in substantially reducing emissions of multiple air pollutants. For particulate matter air pollutants, the implementation of Cambodia's Clean Air Plan would reduce $PM_{2.5}$, PM_{10}, black carbon and organic carbon emissions by 61%, 56%, 63% and 62%, respectively, in 2030 compared to the 2030 baseline scenario emissions. This also represents an absolute reduction in emissions compared to historical (2015) levels. For example, for primary $PM_{2.5}$ emissions, the implementation of Cambodia's Clean Air Plan is estimated to reduce emissions in 2030 by 43% compared to 2015 emission levels. The majority of the particulate matter pollutant emission reductions occur due to the measures included in the Circular on air pollution, but there are also significant reductions associated with implementation of the additional measures included in Cambodia's Clean Air Plan (Fig. 2).

For gaseous pollutants, emissions of VOCs and CO are also substantially reduced through implementation of Cambodia's Clean Air Plan, 80% and 68%, respectively in 2030 compared to the 2030 baseline scenario emissions. Nitrogen oxides emissions are reduced by 48% in 2030 compared to the baseline scenario. The implementation of Cambodia's Clean Air Plan also results in a 19% reduction in CO_2 emissions, contributing to meet Cambodia's Climate Change mitigation goals while at the same time improving air quality.

In terms of individual mitigation measures, switching to cooking using gas stoves in the residential sector, reducing the open burning of waste, and measures on passenger and freight transport (i.e. implementation and enforcement of Euro standards) are the key measures that lead to >10% reductions in one or more particulate pollutants' emissions in 2030 compared to the baseline (Table 13). For VOCs, and CO, controlling emissions from motorcycles is the single measures that accounts for the majority of emission reductions by 2030 from implementing the Clean Air Plan. By contrast, in the transport sector, heavy duty freight vehicles are the largest source of NO_x emissions, and therefore implementation and enforcement of Euro IV standards for freight vehicles was estimated to have the largest effect in reducing NO_x emissions. This was an additional measure added to Cambodia's Clean Air Plan that was not included in the Circular on Air Pollution. Hence the package of measures in Cambodia's Clean Air Plan were needed to target reductions of different air pollutants. The measures to improve energy efficiency and expand renewable electricity generation included in Cambodia's Clean Air Plan from Cambodia Nationally Determined Contribution reduce CO_2 emissions (Table 14). In terms of air pollutant emission reductions, the implementation of these two measures are most effective at reducing emissions of SO_2 emissions, where electricity is the largest source, with smaller reductions in NO_x emissions.

Table 14

Emissions of air pollutants in 2030 for the baseline scenario, and reflecting implementation of all mitigation measures included in this analysis. Emissions are shown as the absolute emissions in 2030 for each scenario, and the percentage reduction in emissions in 2030 compared to the baseline scenario.

Scenario	No.	OC	BC	**PM2.5**	NH3	SO2	PM10	NOx	NMVOC	CO	CO2
Absolute emissions (thousand metric tonnes)											
Baseline 2030		45.0	14.6	98.5	112.0	70.0	132.4	329.0	1119.2	2725.6	40,150.8
Construction Controls	1	45.0	14.6	97.9	112.0	70.0	126.9	329.0	1119.2	2725.6	40,150.8
Euro 4 Buses	14	45.0	14.0	97.4	112.0	70.0	131.3	314.8	1116.7	2718.6	39,884.1
Euro 4 Freight	13	44.7	12.6	94.5	112.0	69.7	128.4	249.2	1109.4	2699.4	39,047.6
Euro 4 cars	6	44.8	14.4	98.1	112.4	69.9	132.0	306.5	1092.9	2521.4	39,715.1
Euro III Motorcycles	4	37.8	12.9	87.4	112.0	70.0	121.3	319.2	457.6	1637.1	39,983.3
Improved Charcoal	12	42.1	14.2	92.8	111.2	68.8	126.7	328.6	1047.0	2512.5	40,150.8
Industrial Emission Controls	7	43.4	13.6	95.3	112.0	70.0	129.1	323.0	1119.2	2725.6	40,150.8
NDC Energy Efficiency	10	44.9	14.5	98.3	112.0	59.5	132.1	323.6	1118.9	2724.8	38,110.4
NDC Renewable Electricity Generation	11	45.0	14.6	98.4	112.0	52.4	132.1	318.0	1119.1	2725.2	35,900.6
Open Waste Burning	8	39.0	13.8	87.4	110.7	69.5	118.9	323.4	1093.5	2682.4	40,150.8
Sulphur Fuel Quality	2	45.0	14.6	98.5	112.0	62.2	132.4	329.0	1119.2	2725.6	40,150.8
Switch biomass to gas stoves	9	35.3	11.8	76.3	109.1	67.4	104.7	321.7	1030.0	2468.8	40,195.8
Switch to public transport	5	45.0	14.6	98.6	112.0	70.0	132.5	329.1	1116.1	2699.5	39,935.0
Tour bus standards	3	45.0	14.6	98.5	112.0	70.0	132.4	329.0	1119.2	2725.6	40,150.8
Air Pollution Circular		22.0	9.3	53.2	108.1	59.0	74.2	286.4	315.9	1127.2	39,420.3
All Measures		17.2	5.3	38.7	107.3	33.5	59.4	171.0	230.7	879.0	32,689.1
Percent reduction vs 2030 baseline											
Construction Controls	1	–	–	0.6	–	–	4.2	–	–	–	–
Euro 4 Buses	14	−0.0	3.7	1.1	–	0.1	0.8	4.3	0.2	0.3	0.7
Euro 4 Freight	13	0.7	13.5	4.1	–	0.5	3.1	24.3	0.9	1.0	2.7
Euro 4 cars	6	0.4	1.4	0.4	−0.3	0.2	0.3	6.8	2.4	7.5	1.1
Euro III Motorcycles	4	16.0	11.3	11.3	0.0	0.1	8.4	3.0	59.1	39.9	0.4
Improved Charcoal	12	6.3	2.9	5.8	0.7	1.8	4.3	0.1	6.5	7.8	–
Industrial Emission Controls	7	3.5	6.3	3.3	–	–	2.5	1.8	–	–	–
NDC Energy_Efficiency	10	0.2	0.3	0.2	0.0	15.0	0.3	1.6	0.0	0.0	5.1
NDC Renewable Electricity Generation	11	0.0	0.0	0.1	0.0	25.2	0.3	3.3	0.0	0.0	10.6
Open Waste Burning	8	13.3	5.1	11.3	1.1	0.8	10.2	1.7	2.3	1.6	–
Sulphur Fuel Quality	2	–	–	–	–	11.1	–	–	–	–	–
Switch biomass to gas stoves	9	21.4	19.0	22.5	2.6	3.8	20.9	2.2	8.0	9.4	−0.1
Switch to public transport	5	0.0	−0.3	−0.1	0.0	0.1	−0.1	−0.1	0.3	1.0	0.5
Tour bus standards	3	–	–	–	–	–	–	–	–	–	–
Air Pollution Circular		51.1	36.4	46.0	3.5	15.8	44.0	12.9	71.8	58.6	1.8
All Measures		61.7	63.4	60.7	4.2	52.1	55.2	48.0	79.4	67.8	18.6

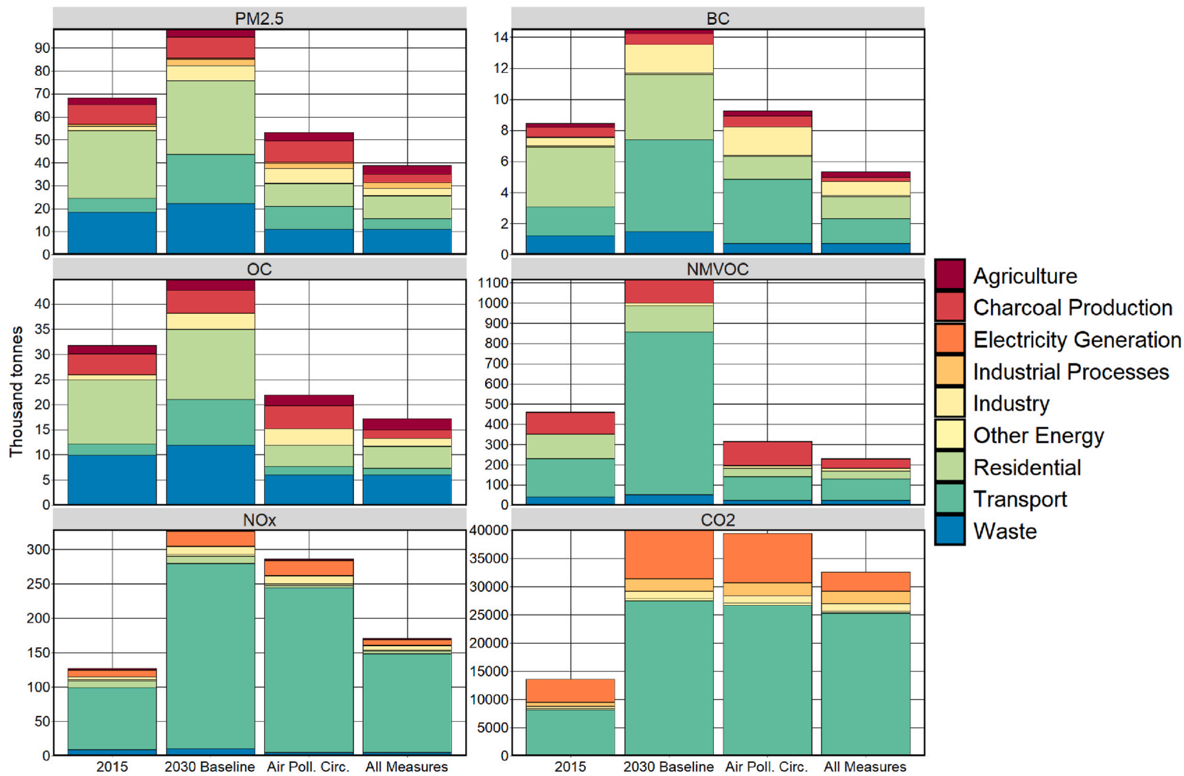

Fig. 2. Emissions of a) $PM_{2.5}$, b) black carbon, c) organic carbon, d) volatile organic compounds, e) nitrogen oxides, and f) carbon dioxide in 2015 and 2030 for the baseline, and mitigation scenario reflecting implementation of the Circular on air pollution and all mitigation measures.

3.3. Health benefits from Cambodia's Clean Air Plan

In 2015 population-weighted annual average $PM_{2.5}$ concentrations were estimated to be ~21 μg m-3 in Cambodia (Fig. 3), more than four times the World Health Organisation air quality guideline (WHO, 2021). A large fraction of this $PM_{2.5}$ concentration was estimated to result from emissions in other countries that are transported to Cambodia, with 22% of $PM_{2.5}$ exposure estimated to result from national emissions (Fig. 3). This total exposure to $PM_{2.5}$ concentrations was estimated to result in 3100 (95% Confidence Intervals (C.I.): 1850–4200) premature deaths in 2015 (Fig. 3), primarily affecting older adults, but also resulting in ~500 (245–724) infant deaths in 2015, 17% of the total mortality burden. In the baseline projection, both annual $PM_{2.5}$ exposure, and premature deaths were estimated to increase in 2030 compared to 2015 levels, with an annual exposure of 24 μg m^{-3} in 2030 in the baseline scenario, 14% greater than 2015 levels (Fig. 3). Premature deaths were projected to increase to 5700 (3400–7700) per year in 2030, an 83% increase. The larger relative increase in health burden from air pollution exposure compared to the increase in $PM_{2.5}$ concentrations is due to the larger, and older population exposed to air pollution in 2030 compared to 2015 levels.

The full implementation of Cambodia's Clean Air Plan was estimated to reduce population-weighted $PM_{2.5}$ concentrations by 4 μg m^{-3} in 2030 compared to the baseline scenario. This is a 17% reduction in total population-weighted $PM_{2.5}$ concentrations in 2030 compared to the baseline scenario (Fig. 3), and a 57% reduction in the national contribution to $PM_{2.5}$ concentrations in Cambodia. This reduction in $PM_{2.5}$ concentrations across Cambodia would avoid an estimated 878

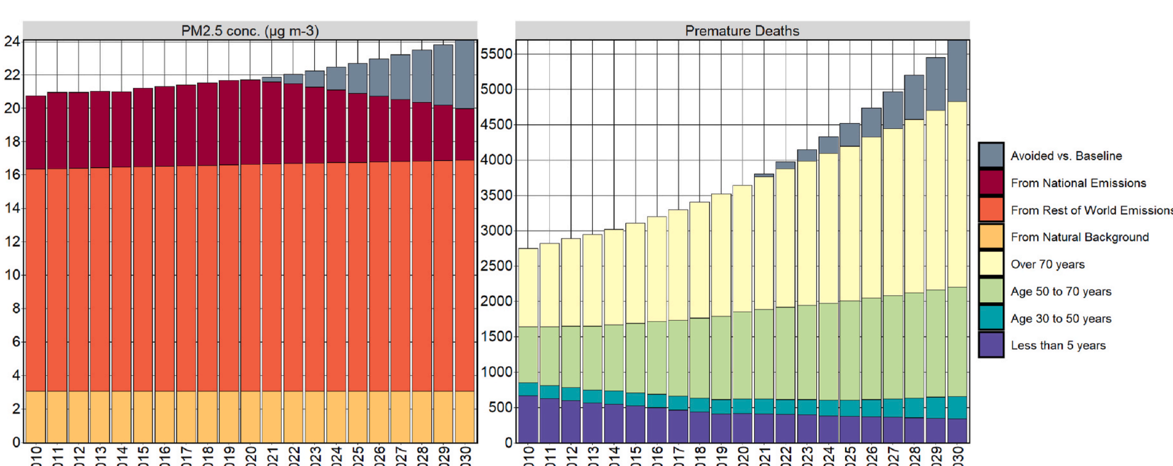

Fig. 3. Change in a) population-weighted annual average ambient $PM_{2.5}$ concentrations across Cambodia and b) premature deaths attributable to ambient $PM_{2.5}$ concentrations from implementation of all measures included in Cambodia's Clean Air Plan.

(530–1200) premature deaths per year, 15% of the total health burden from air pollution, and 57% of the health burden caused by emissions from Cambodia.

4. Discussion

4.1. Implications for improving air quality in Cambodia

Cambodia's Clean Air Plan is the first comprehensive set of actions to reduce air pollutant emissions and improve air quality that has been developed in Cambodia based on an air pollutant mitigation assessment (Ministry of Environment of Cambodia, 2022). The key conclusion from this work is that the actions included in the Circular are effective at reducing air pollutant emissions, and lead to between 12% and 70% reductions in gaseous and particulate matter air pollutants emissions in 2030 compared to the baseline emission projection. The measures relating to implementing Euro IV standards for passenger transport (motorcycles, buses and cars), and reducing the open burning of waste are the measures in the Circular that are most effective in reducing emissions. However, there are also key emission sources, and sub-sectors, where mitigation measures targeting these sources are not identified in the Circular, and where additional mitigation measures included in the Clean Air Plan are effective at further reducing emissions from these sources.

One such source is residential cooking using wood and biomass. The residential sector makes a large contribution to emissions of particulate matter pollutants, and VOCs and CO. However, the Circular includes no action on residential sector air pollutant emissions. Cambodia's Climate Change Strategic Plan 2014–2023 includes two actions in the residential sector, to switch households to use more efficient biomass stoves, and to switch households to cooking using gas or other clean fuels (e.g. electricity). This measure was incorporated into Cambodia's Clean Air Plan as a result of the large reductions in $PM_{2.5}$ and other particulate and gaseous pollutant emissions that are reduced from its implementation. For the majority of air pollutants included in this study, the measure to switch households from biomass to cleaner fuels for cooking was the single measure that led to the largest reduction in national total emissions.

The effectiveness of the residential sector measures at reducing air pollutant emissions is twofold. First, it reduces emissions at the point of fuel combustion in households for cooking. Secondly, where the fuel displaced or reduced is charcoal, emissions are also reduced from the charcoal production process. The benefits in terms of reducing exposure to air pollutants are also twofold. Firstly, as for the other measures included in Cambodia's Clean Air Plan, exposure to ambient air pollution will be reduced through the reduction in emissions in the Residential sector. The majority of households cooking using biomass currently are in rural areas (79% of rural households use firewood for cooking in 2017, and 7% use charcoal (National Institute of Statistics, 2018)). The magnitude of residential air pollutant emissions in Phnom Penh is relatively low, due to the relatively small number of households cooking using biomass (11.7% of households using wood or charcoal in Phnom Penh). However, in other urban areas, a much larger fraction of households cooking using wood (35.6%) or charcoal (17.2%). Therefore, in Cambodian cities outside Phnom Penh, the implementation of measures to switch to cooking using cleaner fuels could make a substantial contribution to improving urban air quality, as well as air quality in rural areas. Secondly, the implementation of measures in the residential sector would also reduce household air pollution exposure, and associated health impacts that occur specifically in households cooing using biomass fuels, which have been estimated to be 14,000 premature deaths per year in 2019 (Murray et al., 2020). In addition, other benefits could include reducing net CO_2 emissions from forests due to reduction in the extraction of wood for residential cooking from Cambodia's forests, enhancing and protecting carbon sinks (Bailis et al., 2017). Therefore, the inclusion of mitigation measures to reduce emissions from the residential sector is a key additional set of actions necessary to improve air quality in Cambodia.

Freight transport is also a major air pollutant emission source not covered in the Circular. In the Circular, mitigation measures are included that are effective in reducing emissions from passenger transport, including implementation and enforcement of Euro 4 standards for motorcycles, buses and passenger cars. However, the key source of BC and NOx emissions from transport come from heavy duty freight transport. The extension of Euro 4 standards to heavy-duty freight vehicles was shown to substantially increase the emission reductions that can be achieved from action in the transport sector, particularly for BC and NO_x, where national total emissions are reduced by 13.5% and 24% in 2030, respectively, compared to the baseline scenario emissions in 2030. The inclusion of this mitigation measure in Cambodia's Clean Air Plan therefore extends the Plan to cover a larger fraction of national total air pollutant emissions, and lead to greater reductions in emissions compared to the measures included in the Circular.

In the transport sector, in addition to the implementation of vehicle emission standards for internal combustion engine vehicles using diesel and gasoline, other mitigation measures, not included in Cambodia's Clean Air Plan, could also contribute to reducing air pollutant emissions. For example, increasing the fraction of electric, or other low emission vehicles in the vehicle fleet could eliminate exhaust air pollutant emissions, alongside also reducing greenhouse gases like CO_2. However, electric vehicles may continue to produce air pollution through non-exhaust emissions (e.g. tyre and brake wear and road dust resuspension), and through increased electricity generation from fossil or biomass fuels (UNEP, 2019). Electromobility, and other additional air pollutant mitigation measures may therefore be considered in updated Clean Air Plans, in which appropriate targets, and implementation pathways for these measures are developed.

4.2. Uncertainties, limitations and future improvements

Due to data limitations, assumptions were made to estimate comprehensively historic air pollutant emissions, and to project them into the future. The emission reduction assessment was undertaken so that it could be regularly updated, as new data becomes available. Therefore, the limitations identified provide a focus for future updates to the air pollutant emission estimates and mitigation potential during the implementation period of the Clean Air Plan. The Clean Air Plan specifically identifies the development and regular updating of a national air pollutant emission inventory as a key part of the Plan's implementation (Ministry of Environment of Cambodia, 2022).

For key source sectors, such as residential, transport and open waste burning, relatively disaggregated characterisations of the sources of air pollutant emissions within these sectors were made. For example, for residential and waste emissions, estimates were made separately for Phnom Penh and other regions. For the transport sector, sufficient data was available for a detailed disaggregation of emissions between vehicle types, fuels and Euro standards for road transport. For these sources where relatively detailed modelling was possible due to the availability of sufficient national data, the key future improvements to the estimation of air pollutant emissions are the inclusion of country-specific emission factors to estimate the rate of emissions from these sources based on the specific conditions in which fuel is combusted from these sources in Cambodia. Due to a lack of country-specific emission factors, international default emission factors were applied (EMEP/EEA, 2019), which may not account for the specific condition of the vehicles, and driving conditions within Cambodia.

For other sources, in particular industry and commercial and public services, there was a lack of national data to disaggregate emissions into individual sources within these sectors. Therefore, emissions were estimated only for the overall sector, disaggregated by fuel (Section 2). A key improvement is therefore the development of a more disaggregated assessment of emissions from sources within industry and commercial and public services. For example, within the industry sector, different fuels may be consumed by different machinery, with different efficiencies and emission control technology fitted to them. Similarly, in commercial and public services, consumption of fuels in restaurants, schools, hospitals and businesses may result in different emissions due to the different technologies in which the fuels are being burned. In addition, Cambodia's Clean Air Plan includes the development and enforcement of emission standards for industries. The implementation of these standards was modelled as an aggregate reduction in the industrial sector. A more disaggregated characterisation of the industrial and/or commercial sector to quantify emissions for particular sub-sectors (e.g. particular industrial subsectors, and/or industries in different geographic regions) would allow for the assessment of implementation of sub-sector specific emission standards to be modelled, and their impact on air pollutant emissions.

Additionally, within the industrial and commercial sectors, there were also missing sources of emissions and fuel consumption that were not quantified due to their lack of inclusion in national statistics. For example, in the commercial sector consumption of wood and charcoal was not included, but may occur within commercial enterprises such as food vending (Batchelor, 2021). The consumption of wood and charcoal within the commercial sector is likely to be an informal activity and is not captured in the national energy balance statistics used to quantify air pollutant emissions from this sector. Therefore, additional primary data collection in the industrial and commercial sectors to i) disaggregate available fuel consumption statistics between industrial and commercial subsectors, and ii) identify sources and magnitudes of fuel consumption not currently included in national statistics would substantially improve the characterisation of emissions from these sectors, and the evaluation of mitigation options.

The assessment of the consequences of changes in air pollutant emissions from implementation of measures in Cambodia's Clean Air Plan on annual average population-weighted $PM_{2.5}$ concentrations and attributable health impacts was based on the application of linearised coefficients from the GEOS-Chem model developed at the global scale (Kuylenstierna et al., 2020). These coefficients quantify the sensitivity of national $PM_{2.5}$ concentrations to changes in emissions across $2^\circ \times 2.5^\circ$ grids globally. Limitations associated with their application are that atmospheric chemistry and transport is only represented at a coarse global grid resolution, and therefore finer scale transport and chemical reactivity is not captured within these coefficients. Applying these linearised coefficients assume that a change in $PM_{2.5}$-precursor emissions in a grid results in a linear change in annual average population-weighted $PM_{2.5}$ concentrations in Cambodia. Therefore, non-linear interactions between, e.g. SO_2, NH_3 and NO_x to form secondary inorganic aerosol, are not represented in the application of these coefficients, as previously discussed in Kuylenstierna et al. (2020).

The approximately 900 (95% C.I.: 530–1200) avoided premature deaths per year estimated by 2030 through implementation of Cambodia's Clean Air Plan is likely an underestimate of the scale of the health benefits that could result from implementing the Plan. In this study, only the health benefits from exposure to ambient air pollution were estimated, but did not include formation of secondary organic aerosol, which contributes ~15% of ambient $PM_{2.5}$ mass (Nault et al., 2020). The implementation of the Plan would also reduce exposure to household air pollution for those transitioning from cooking using traditional biomass stoves, increasing the avoided health impacts from household air pollution exposure. Additionally, exposure to $PM_{2.5}$ is also associated with a range of non-fatal health outcomes, such as adverse pregnancy outcomes (Malley et al., 2017), and asthma exacerbations (Anenberg et al., 2018). Finally, the implementation of the Clean Air Plan would also impact exposure to other health-damaging air pollutants, such as ground-level ozone, and nitrogen oxides, due to the reduction in the emissions, and emissions of ozone precursors. These other pollutants are also associated with negative health outcomes (Lefohn et al., 2018; Malley et al., 2017), and the health benefits from reduction in exposure to these pollutants was not considered in this work.

5. Conclusions

Low- and middle-income countries experience the largest burden of disease associated with exposure to air pollution, but often have the limited data to identify the contribution of major sources, and the strategies and actions that could be taken to alleviate these health impacts. Since 2000, the Kingdom of Cambodia has had regulations for the control of emissions of air pollutants and concentrations in the atmosphere, but rapid economic development has led to increased emissions and poorer air quality. In 2020, the Prime Minister of the Royal Government of Cambodia outlined a set of actions in a Circular on air pollution to improve air quality across the country, but the impact of these actions was not quantified. Building on this Circular, the Ministry of Environment of Cambodia developed the country's first Clean Air Plan, designed to provide a clear roadmap to reduce air pollutant emissions, exposure and improve human health.

This study provides the first quantitative assessment of air pollutant emission reductions in Cambodia that underpins the air pollution mitigation actions included in Cambodia's first Clean Air Plan. The assessment highlights that currently, nationally emissions of air pollutants are dominated by residential, transport and waste burning emissions, as well as electricity generation, and other smaller sources such as industry. In the absence of actions to control air pollutant emissions, the magnitude of air pollutant emissions are projected to increase substantially into the future to 2030. However, implementation of the 15 mitigation measures included in Cambodia's Clean Air Plan were estimated to reduce air pollutant emission substantially compared to current levels and future baseline projections. These actions were estimated to avoid approximately 900 avoided premature deaths in 2030 compared to the baseline scenario due to reductions in ambient air pollution. The benefits of implementing these actions on human health are likely broader, due to reductions in household exposure to air pollution and reductions in the incidence of non-fatal health impacts that were not quantified in this study.

Finally, as Cambodia implements its Clean Air Plan, this mitigation assessment also provides the basis for monitoring its effectiveness. The integration of additional data as it becomes available into the modelling framework provides the basis for updating the air pollutant emission estimates in future years to track progress on implementing the Clean Air Plan. This ability to update the air pollution mitigation assessment also provides the basis for reviewing, refining and revising the Clean Air Plan to identify more specific mitigation actions in particular sources, and identifying the next phase of mitigation actions that should be implemented at the time when the Clean Air Plan is revised.

Author contribution

Pak Sokharavuth: Conceptualization, Writing – drafting, reviewing & editing, Sophearith Thiv: Conceptualization, Writing – drafting, reviewing & editing, Chea Nara: Conceptualization, Writing – drafting, reviewing & editing, Chandath Him: Conceptualization, Methodology, Software, Formal analysis, Writing – drafting, reviewing & editing, Sam Sokyimeng: Conceptualization, Methodology, Software, Formal analysis, Writing – drafting, reviewing & editing, Daven K. Henze: Methodology, Software Writing –reviewing & editing, Ryan Holmes: Methodology, Formal analysis, Writing –reviewing & editing, Johan C.I. Kuylenstierna, Christopher S. Malley: Conceptualization, Methodology, Software, Formal analysis, Writing – drafting, reviewing & editing, Eleni Michalopoulou: Methodology, Formal analysis, Writing –reviewing & editing, Jessica Slater: Methodology, Formal analysis, Writing –reviewing & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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