# The Importance of Long-Range and Local Emission Sources for Mitigating the Potential Health Impact of Airborne Particulate Matter in Thailand

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# Abstract

The negative health impacts of particulate matter (PM) air pollution are associated with long-term exposure, most commonly quantified by the annual average $PM_{10}$ or $PM_{2.5}$ concentrations. The Thai government has set air quality standards to protect public health based on these. This study explores the relative importance of local to regional emission sources in determining annual average of PM concentrations across Thailand using both measurement and modelling approaches.

Firstly, a chemical climatology approach is used to explore the contribution of biomass burning episodes to the annual average $PM_{10}$ concentrations between 2011 and 2015. In Northern Thailand, biomass-burning events result in short-term peak $PM_{10}$ concentrations that influence annual $PM_{10}$ concentrations and lead to exceedance of standards. The highest hourly $PM_{10}$ concentrations occurred predominantly in March contributing 15-20% to the annual mean. In contrast, in Southern Thailand results show that biomass burning events can result in elevated hourly $PM_{10}$ concentrations with a very small effect on annual $PM_{10}$ concentrations (<5%).

Secondly, different types of location in Bangkok and central Thailand were analysed to understand how these contribute to PM concentrations. There was greater variation in annual average $PM_{10}$ concentrations at Bangkok roadside sites (26 to 63 $\mu g\ m^{-3}$) compared to between at general sites in Bangkok (24 to 48 $\mu g\ m^{-3}$). At sites exceeding the Thai national standard of 50 $\mu g\ m^{-3}$, large local emission sources are important in causing exceedance of the annual $PM_{10}$ standard.

Lastly, to understand how future emissions will influence $PM_{2.5}$ concentrations and human health, the study develops an emission inventory of all relevant pollutants for 2010 and future scenarios to estimate how these emissions will change up to 2030. The findings show that the expected increases in annual $PM_{2.5}$ concentrations can be avoided if current government plans are fully implemented, but additional actions are needed as well.

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# Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References

Signed

Ruchirek Ratchaburi

# Chapter 1: Introduction

## 1.1 Air quality and its impact

Air pollution, defined as contamination of the indoor or outdoor air by a range of gases and solid particles that modify its natural characteristics, has been identified as a global health priority by the World Health Organisation (WHO, 2016). The risk of air pollution in terms of environment and human health impacts has been identified as a priority in recent decades in many countries across the world (Kuklinska, Wolska, and Namiesnik, 2015). The air pollution from both outdoor (ambient) and indoor (household) sources represents the largest environmental risk factor to human health, according to the WHO accounting for 7 million premature deaths around the world every year from respiratory and cardiovascular diseases, and lung cancer (WHO, 2016). Air pollution also causes a range of other negative health impacts. In addition to the health impacts, there are many other negative impacts of air pollution, including decreasing agricultural crop yields, reducing biomass growth of forests and other natural vegetation, reducing ecosystem biodiversity and degrading national heritage (Ashmore, 2005).

The negative impacts of air pollution are reflected in the UN Sustainable Development Goals (SDGs), although air pollution itself does not have its own specific goal (UN, 2019). Efforts to combat air pollution contribute to SDG 3 (good health and well-being), SDG target 7.2 (access to clean energy in the home), SDG target 11.6 (air quality in cities), SDG target 11.2 (access to sustainable transport) and SDG 13 on climate action. In addition, actions to mitigation air pollution have also been shown to make a contribution to meeting the goals of the Paris Agreement on climate change, through the simultaneous reduction of greenhouse gases that occur when action is taken on key air pollution and greenhouse gas sources (e.g. industry of electricity generation) (UN, 2015).

Air pollution is not a single substance. There are many chemicals that are released into the atmosphere that have been categorised as air pollutants. The United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP) considers 25 substances as air pollutants that are to be reported by signatories to the Convention. These include substances categorised as i) ‘Main Pollutants’

which includes nitrogen oxides ($NO_x$), non-methane volatile organic compounds (NMVOC), sulphur oxides ($SO_2$) and ammonia ($NH_3$), ii) Particulate Matter (PM), iii) carbon monoxide (CO), iv) Heavy metals, and v) persistent organic pollutants (POPs) (UNECE, 2003).

This thesis focusses exclusively on particulate matter air pollution (abbreviated to PM). PM is the pollutant that is most strongly associated with negative health impacts (REVIHAAP, 2013). In addition, in Thailand (the geographic focus of this thesis), particulate matter substantially exceeds World Health Organisation (WHO) guidelines for PM concentrations for the protection of human health, and in some areas exceeds Thai National Air Quality standards (PCD, 2015). The overall aim of this thesis is to understand how atmospheric emission sources influence the variation in PM concentrations across Thailand that contribute to the annual average PM concentrations in different locations. The annual average PM concentration is suitable for estimating long-term exposure of populations to PM, and is the metric for quantifying PM concentrations that is most associated with negative health outcomes (REVIHAAP, 2013). In addition, this thesis aims to understand the drivers of the variation in annual PM concentrations across Thailand, and to identify key strategies to reduce PM, to protect human health.

This Chapter aims to provide the necessary background information on PM and its role in damaging human health, its source and strategies for mitigation globally to inform on the research presented in Chapters 3, 4 and 5. It also reviews the current state of knowledge on PM in Thailand, what gaps remain, and how they inform the research questions answered in this thesis. Section 1.2 therefore describes particulate matter, and the different substances that contribute to its formation. Section 1.3 describes the major sources of air pollution globally, including major source sectors, as well as geographic sources and the contribution from the long-range transport of emissions. Section 1.4 then reviews the health impacts of particulate matter and the key metrics that use to estimate the severity of PM exposure relevant for human health. Section 1.5 summarises how to quantify the annual average PM concentrations. Section 1.6 describes the study area of Thailand. Section 1.7 then outlines the state of knowledge of PM in Thailand. Section 1.8 describes current gaps in knowledge and the research questions that will be explored in this thesis, and finally Section 1.9 Chapter Outline.

## 1.2 Particulate matter

Particulate matter (PM) may be considered as a solid or liquid or a mixture of both phases and can be primary or secondary particles (AQEG, 2005). Primary PM is directly emitted as solid or liquid particulates into the atmosphere, while secondary PM are solid or liquid particles formed in the atmosphere through chemical reactions involving primary pollutants emitted as gases. PM is not just one substance, but is made up of a variety of different chemicals in solid and liquid phase. There are two broad modes of formation of particulate matter. The first is particles that are directly emitted into the atmosphere. These 'primary particles' are emitted directly into the atmosphere from different sources such as road dust, wind-blown dust, sea salt, and combustion-generated particles such as fly ash and soot, also includes particles formed during combustion. Primary particles may themselves be different substances, including black or elemental carbon, organic carbon, or soil dust. 'Secondary particles' are formed by 'chemical reaction involving gas-phase precursors in the atmosphere or by other processes involving chemical reactions of free, adsorbed, or dissolved gases' (U.S. EPA, 1996), The gas phase pollutants that contribute to secondary formation of particulate matter include nitrogen oxides (NOx), sulphur dioxide ($SO_2$) and ammonia ($NH_3$), which react and combine to form 'secondary inorganic aerosol', and volatile organic compounds (VOCs), which react in the atmosphere to form secondary organic aerosol. These various sources of primary and secondary pollutants are shown in Figure 1.1.

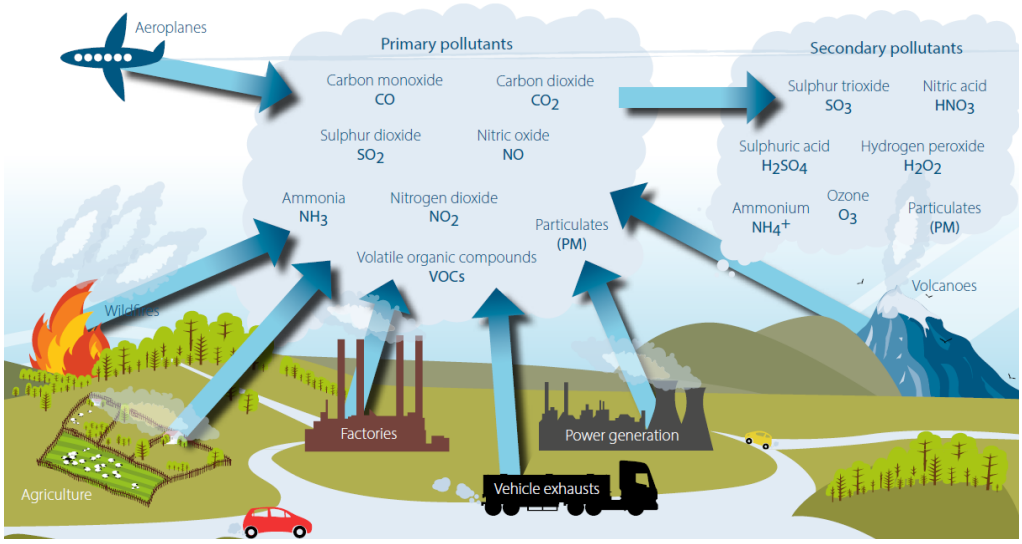



**Figure 1.1:** Sources of primary and secondary pollutants (SEPA, 2019)

Particulate matter is made up of particles of different sizes. To categorise PM of different sizes, for measurement of PM in the atmosphere, and for assessment of health effects, various different metrics to quantify PM concentrations have been used. PM for this study focuses on $PM_{10}$ and $PM_{2.5}$ (Particulate Matter with an aerodynamic diameter of less than 10 and 2.5 microns respectively). Figure 1.2 shows a size comparison between human hair and PM particles, a single hair on average is 50-70 micrometers in diameter (U.S. EPA, 2018), that means it is 20-28 times wider than $PM_{2.5}$, and 5-7 times wider than $PM_{10}$. The following sub-sections describe in more detail these different components of PM, their properties and key characteristics. This study notes that other metrics quantifying PM have been defined, including total suspended particulates (TSP), which encompasses all size fractions of PM in the atmosphere, as well as ultrafine particles (with a diameter less than 100 nanometres). These other size fractions of PM are not considered in detail in this study because i) of a lack of in-situ monitoring of particles in these size fractions in Thailand, and ii) because of the greater evidence of negative health impacts associated with the $PM_{2.5}$ and $PM_{10}$ metrics compared to TSP and ultrafine particles (REVIHAAP, 2013).

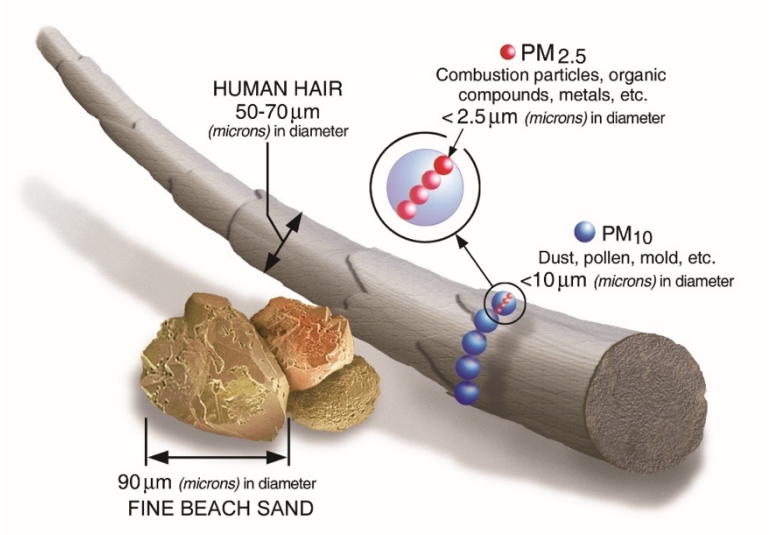



**Figure 1.2:** A size comparison between human hair and PM particles (U.S. EPA, 2018)

### 1.2.1 Primary particulate matter

## 1) Black Carbon

Black or elemental Carbon (BC) is a primary pollutant contributing to PM concentrations. In Europe, it contributes up to 20% of particulate matter composition at urban traffic sites, but in many locations its contribution is much smaller (Putaud *et al.*, 2010). There is evidence that black carbon is a particle with toxicity that is associated with health effects that are distinct from the total mass of $PM_{2.5}$. The WHO concluded that exposures to black carbon for both short-term (24 hours) and long-term (annual) are linked with cardiovascular disease and premature mortality (WHO, 2013). According to the Intergovernmental Panel on Climate Change, BC is the third largest contributor to global temperature increases, due to direct absorption of incoming solar radiation, in addition to indirect climate effects such as interaction with clouds, and deposition on snow and ice (U.S. EPA, 2012a). Black carbon is formed by the incomplete combustion of fossil fuels, biofuels, and biomass, in particular through diesel vehicles (WHO, 2011).

## 2) Organic Carbon

Organic Carbon (OC) is a major source of PM and is also a primary pollutant emitted from various sources through incomplete combustion. Organic carbon is therefore emitted from many of the same sources on black carbon. In addition, organic carbon can also be a secondary pollutant formed form a variety of precursor emissions (Seinfeld and Pandis, 1998). Organic carbon generally refers to the mix of compounds containing carbon bound with other elements like hydrogen or oxygen. Organic carbon may be a product of incomplete combustion, or formed through the oxidation of VOCs in the atmosphere. Both primary and secondary OC possess radiative properties that fall along a continuum from light-absorbing to light-scattering (U.S. EPA, 2012a).

### 1.2.2 Other primary particulate matter

Other pollutants also contribute to PM. These include heavy metals and polycyclic aromatic hydrocarbons (PAHs). However, these other substances make a small contribution to the total mass of PM in the atmosphere. As shown in Section 1.3, from previous studies, it is the mass of PM that is the primary determinant/metric for its impact on human health, and therefore these substances are not considered as individual components of PM in this thesis.

### 1.2.3 Secondary particulate matter

In addition to primary emissions of PM, secondary PM is formed through chemical reactions of gaseous precursors that are directly emitted. The formation of secondary PM can be grouped into two main categories, the formation of secondary inorganic aerosol and the formation of secondary organic aerosol.

#### 1.2.3.1 Secondary inorganic aerosol

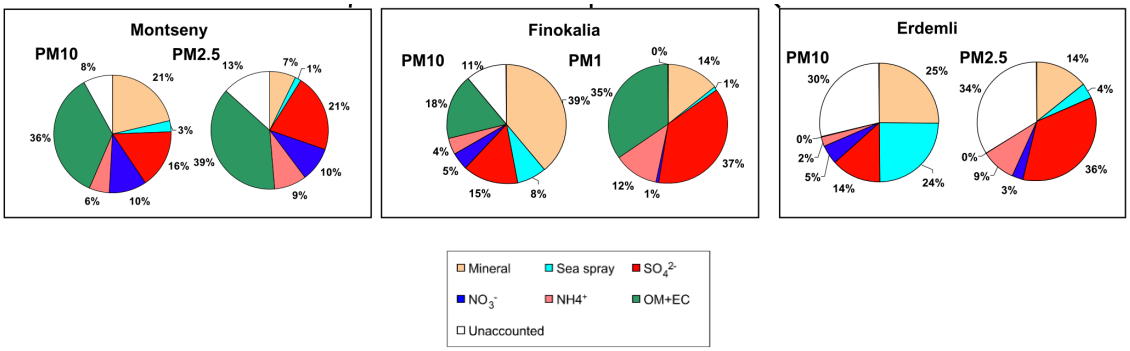
Secondary inorganic aerosol is formed through the chemical reaction of inorganic gaseous emissions in the atmosphere to form inorganic ions in the particulate phase. Both anthropogenic and natural emissions contribute to the formation of secondary inorganic aerosol. Natural sources of inorganic aerosol include 'sea salt', i.e. sodium chloride, as well as natural sources of $NO_x$ (e.g. lightning), $SO_2$ (e.g. volcanic eruptions), and $NH_3$ (wild animals). Anthropogenic sources of inorganic aerosol result from anthropogenic sources of $NO_x$, $SO_2$ and $NH_3$. In the atmosphere, secondary inorganic aerosol is formed through the reaction of these three gases to form ammonium nitrate ($NH_3$ and $NO_x$) and ammonium sulphate ($NH_3$ and $SO_2$). The formation of ammonium nitrate is controlled by the rate of conversion of $NO_2$ to nitric acid ($HNO_3$) through reaction with the hydroxyl radical (Jenkin and Clemitshaw, 2000). The availability of $NH_3$ to react with nitric acid (formed from $NO_x$ emissions) and sulphuric acid (formed in the atmosphere from $SO_2$ emissions) to form ammonium nitrate and ammonium sulphate, respectively, can control the rate of formation of secondary inorganic aerosol, respectively (Fuzzi et al., 2015). The conversion of gaseous ammonia to ammonium is strongly influenced by temperature, with lower temperature favouring the formation of secondary inorganic aerosol, and

higher temperatures resulting in a shift in the equilibrium towards the gaseous phase (Koziel, 2006; Meng *et al.*, 2018). Further detail on the individual anthropogenic precursors of secondary inorganic aerosol are provided in the following sub-sections.

# 1) Ammonia

Ammonia ($NH_3$) makes a significant contribution to the formation of secondary inorganic aerosols (SIA) (Li et al., 2016; Kirkby et al., 2011). The SIA e.g. ammonium sulfate ($(NH_4)_2SO_4$) and ammonium nitrate ($NH_4NO_3$) plays an increasingly important role in $PM_{2.5}$ pollution because $NH_3$ is a precursor gas for SIA, especially during severe haze episodes (Huang et al., 2014; Tao et al., 2014). Previous studies that assessed the major factors controlling levels of $PM_{10}$ and $PM_{2.5}$ in the regional background from Montseny, Finokalia (Greece) and Erdemli (Turkey) for the period 2001 to 2008 found that ammonium concentrations represents 2–4% of $PM_{10}$ and 9–12% of $PM_{2.5}$ (Querol *et al.*, 2009) as shown in Figure 1.3 (a). Another study showed that the fertilizer application and manure management from the agricultural sector are the largest sources of $NH_3$ emissions as presented in Figure 1.3 (b) (Carnell *et al.*, 2017; Xu *et al.*; 2015, Yan et al., 2003), the emissions mainly come from agricultural source contributing to $PM_{2.5}$ concentrations (Zhao *et al.*, 2017; Wu et al., 2016).

(a)




(b)

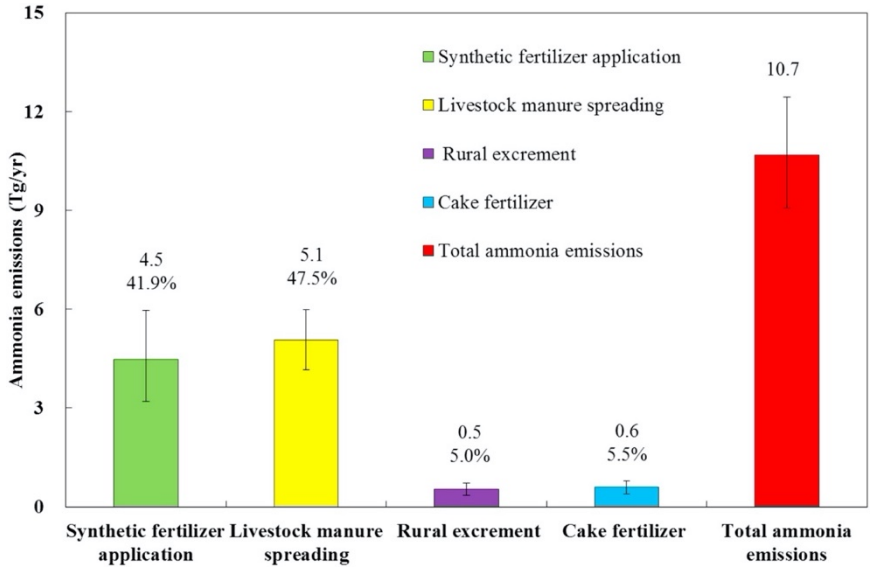



**Figure 1.3:** (a) The mean annual levels of $PM_{10}$ and $PM_{2.5}$ data captures measured at rural-regional background sites (Querol *et al.*, 2009) (b) $NH_3$ emissions from agricultural source (Xu et al., 2015)

## 2) Nitrogen oxides

Nitrogen oxides ($NO_x$) refers to a group of pollutants, made up of nitrogen oxide (NO) and nitrogen dioxide ($NO_2$). NOx is a major precursor of fine secondary PM that contributes to the formation of secondary inorganic aerosol, through formation of ammonia nitrate (see above for ammonia) (U.S. EPA, 1996). While $NO_x$ as a gas is an air pollutant with effects on respiratory health, its role in the formation of PM also contributes to its negative human health effects (WHO, 2016). Sources of NOx, mainly come from road traffic and electricity generation. During fuel combustion, nitrogen in fuels is converted to oxides of nitrogen in the combustion process with high-temperature combustion to form oxides of nitrogen (WHO, 2006). A study in Thailand investigated

the emission inventory of on-road transport in Bangkok Metropolitan Region (BMR) during the period from 2007 to 2015 found that truck is identified as a major contributor of $NO_X$, $SO_2$ and PM (Cheewaphongphan *et al.*, 2017).

## 3) Sulphur dioxide

Sulphur dioxide ($SO_2$) also is a major precursor of fine secondary PM (U.S. EPA, 1996), and is a primary air pollutant. The major source of $SO_2$ is from the fossil fuel (coal and oil) combustion, which contains varying amounts of sulphur, unabated burning of coal and the use of fuel oils and automotive diesel with a higher sulphur content (WHO, 2006). The $SO_2$ emission of on-road transport in the Bangkok Metropolitan Region (BMR), Thailand mainly comes from trucks (Cheewaphongphan *et al.*, 2017).

### 1.2.3.2 Secondary organic aerosol

In addition to the secondary inorganic aerosol described in the previous section, the other mechanism for the formation of particulate matter from gaseous precursors is the formation of secondary organic aerosol from volatile organic compounds and intermediate volatility organic compounds (IVOCs). Sources of VOCs and IVOCs include both natural and anthropogenic sources. Natural sources of VOCs include emissions from vegetation, while anthropogenic sources include a range of combustion activities, including in the transport, residential, industrial and other sectors. Recent reviews have highlighted the greater uncertainty of the atmospheric processing involved in the formation of secondary organic aerosol compared to secondary inorganic aerosol (Fuzzi *et al.*, 2015). This uncertainty results from the large number of organic compounds that make up the organic aerosol fraction, only a small fraction of which have been characterised and quantified (Fuzzi *et al.*, 2015), and therefore the large number of chemical reactions governing the formation of secondary organic aerosol from gaseous precursors. It also results from uncertainty in the emission levels of volatile organic compounds, and intermediately-volatile organic compounds from different sources. This results in challenges in atmospheric models accurately representing the levels of organic aerosol observed in different regions, and therefore designing effective strategies to control organic aerosol, which can comprise up to 40% of the total PM concentration in some locations.

# 1.3 Source of particulate matter

## 1.3.1 Source sectors

PM, and PM precursor emissions are emitted from a range of human activities, as well as from natural sources, and the sources of different air pollutants very between countries depending on major economic activities in each country. The International Energy Agency (IEA) reported that, globally, the energy sector has the largest sources of anthropogenic emissions of a range of air pollutants, as shown in Figure 1.4. Figure 1.4 shows 85% of primary PM comes from the energy sector (approximately 50% from buildings: cooking, heating and lighting, 20% from industry: fuel combustion and process emissions, 10% from transport combustion: exhaust, brake and tyre and road wear and fuel evaporation, 3% from power plant: combustion of coal, oil, gas, bioenergy and waste, 2% from fuel supply: extraction, storage, transport and transformation of fossil fuels, and 15% from non-energy: agriculture, solvents and waste). Moreover, air pollution emissions from different sectors show that the main source of $SO_2$ emissions are the power plant and industry sectors, $NO_x$ emissions are predominantly from transport and $NH_3$ emissions mainly comes from the non-energy sector (agriculture) (IEA, 2016).

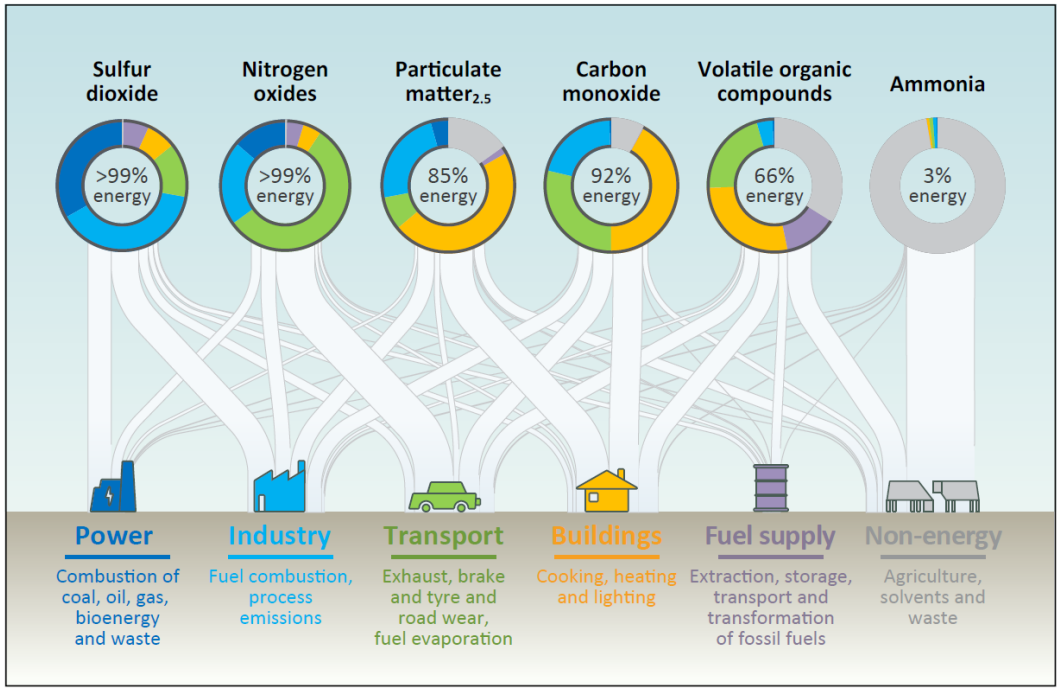



**Figure 1.4:** Primary air pollutants and their sources (IEA, 2016)

In addition to the multiple anthropogenic sources of PM and PM precursor emissions, the natural emission sources include wind-blown desert dust, sea spray aerosols, volcanoes and seismic activities, fires are caused by burning forests and other vegetation, excluding agricultural burning of stubbles etc. (EEA, 2012). In Thailand, the main sources of these pollutants were identified as activities that required energy consumption, such as land transportation, electricity generation and industry (PCD, 2015). A recent study by Thepnuan *et al.* (2019) identified that biomass burning from forest and agricultural waste burning in Chiang Mai province, Thailand (the Northern part of Southeast Asia) was also the major source (37%) of organic compounds in the $PM_{2.5}$ aerosols during smoke haze period in 2016.

## 1.3.2 Geographic sources of emissions

In addition to the specific source sectors that emit air pollutants, air pollution levels in a particular location are also determined by emissions that occur on local, national, regional and hemispheric scales through long-range transport (LRT). Determining the spatial scale on which emissions affect air pollution in particular locations is important to determine the most effective methods of mitigation. A useful example that demonstrates the importance of considering emissions at different scales and their effect on PM concentrations in a location is provided by a modelling study conducted for Delhi, India (Amann *et al.*, 2017). This study shows that, even for a polluted megacity of over 10 million inhabitants, approximately 60% of population-weighted $PM_{2.5}$ concentrations in Delhi were determined by emissions occurring outside the city. The major sources of emissions contributing to $PM_{2.5}$ concentrations in Delhi at these different scales are also different. Diesel vehicles and cookstove emissions were the largest source of $PM_{2.5}$ emitted in Delhi itself, while secondary inorganic aerosol made a larger contribution to $PM_{2.5}$ in Delhi formed from emissions emitted outside of Delhi. This underlies the importance of considering contributions to PM on different geographic scales when considering i) how PM concentrations in a particular location are determined from different sources, and ii) the most effective methods to reduce PM concentrations.

In Southeast Asia, the issue of long-range transport of PM emissions is particularly important in the context of emissions from biomass burning. For example, studies have reported that Southeast Asian countries and beyond had air quality and visibility problems

from emission and haze related to forest fires in Indonesia due to the transport of PM emissions thousands of miles from where they were originally emitted (Koe et al., 2001; Thompson et al., 2001). During the peak of the smoke-haze episode in June, 2013, there was over 160,000 ha of burned land in Sumatra with over 80% being deforested peatlands (Gaveau et al., 2014). Another study found that the smoke-haze in June 2013 across Sumatra island in Indonesia was the worst air pollution episode recorded in Singapore, the highest 24-hr moving average $PM_{2.5}$ concentration reached 310 μg $m^{-3}$ (Velasco and Rastan, 2015). Exposure to smoke from wildfires, forest fires, and open-field burning related to agricultural practices is a serious problem in many parts of the world. There is evidence that fires can increase short-term air pollution concentrations not only in those locations where the biomass burning takes place, but in locations distant from the source of emissions (Liu *et al.*, 2015), but the impact of long-range transport of biomass burning emissions on long-term air pollution exposure has been less studied due to the periodic nature of biomass burning episodes (which generally occur during specific times of the year). The long-range transport of emissions from biomass burning also has substantial health impacts associated with it. The annual global mortality attributable to landscape fire smoke was estimated to be 339,000 premature deaths, in sensitivity analyses the interquartile range of all tested estimates was 260,000–600,000 and sub-Saharan Africa (157,000) and Southeast Asia (110,000) were the most affected region (Johnston *et al.*, 2012).

In addition, UNECE (2015) reported that the composition and mass concentrations of $PM_{2.5}$ in Europe are substantially affected by long-range transport (LRT). During LRT episodes, particles can cause adverse health effects far from their emission sources (WHO, 2006). For example, the study for sources of $PM_{2.5}$ from LRT episodes in southern Finland during 1999–2007 using air quality monitoring results, backward air mass trajectories, remote sensing of fire hot spots, transport and dispersion modelling of smoke found that open biomass burning in Eastern Europe causes high fine particle concentration peaks in large areas of Europe almost every year and the highest particle concentrations (maximum 1 hour, mean 163 μg $m^{-3}$) and the longest episodes (9 days) were mainly caused by the emissions from open biomass burning (Niemi *et al.*, 2009).

## 1.4 Health effects of particulate matter

There is widespread evidence for the negative effects of particulate matter on human health, particularly cardiovascular and respiratory diseases. There have been multiple efforts to quantify the overall global burden of disease attributable to particulate matter. These studies have all concluded that air pollution across the world has a significant effect on public health. Exposure to air pollutants has been associated with several adverse health effects and lead to increasing mortality and morbidity (WHO, 2006). In 2016, WHO reported that approximately 3 million people were killed by ambient air pollution annually in all regions across the world (WHO, 2016). However, Western Pacific and South East Asia were the most affected, about 90% of people breathed air that did not comply with the WHO Air Quality Guidelines and more epidemiological studies of the long-term effects of exposure to air pollution in low-income where air pollution reaches unacceptable levels, are urgently needed (WHO, 2016).

The evidence for the negative impacts of air pollution on human health derive from controlled laboratory studies on animals (e.g. Wang *et al.*, 2019) and humans (e.g. Navarro *et al.*, 2019), where decreases in lung function and cardiovascular activity have been reported during exposure to PM (U.S. EPA, 2019a). At a population-scale, epidemiological studies provide comprehensive evidence for the effect of PM on a wide range of different health outcomes (WHO, 2013). Exposure to PM has been shown to be a major cause of increase in hospital admissions for respiratory and cardiovascular diseases (Chang *et al.*, 2005). In North American and Western European countries, many studies investigated the effects of PM for particularly respiratory and cardiovascular diseases on daily mortality, hospital admissions, and emergency department visits (Xiao et al., 2016). The morbidity and mortality from cardiovascular and respiratory diseases might be caused by exposure to air pollutants (Brunekreef and Holgate, 2002). Fewer studies have been conducted in other regions of the world to assess the effect of air pollution on human health, but those epidemiological studies that have been conducted have shown a consistent association between PM exposure and negative respiratory and cardiovascular health impacts (Atkinson *et al.*, 2012).

Many diseases have been associated with exposure to these air pollutants, especially long-term exposure to particulate matter has negative impacts on human health (Kiesewetter *et al.*, 2015). Exposure to $PM_{2.5}$ and $PM_{10}$ has been associated with negative health

effects, including those caused by impacts on respiratory and cardiovascular systems (Chang et al., 2005). Outdoor PM exposure from anthropogenic activities is an important global cause of premature death (Anenberg et al., 2010). Anenberg *et al.* (2018) estimated that in 2015, 5–10 million annual asthma emergency room visits globally could be attributable to $PM_{2.5}$ (4–9% of the annual number of global visits) and the magnitude of the global asthma burden that could be avoided by reducing ambient air pollution of $PM_{2.5}$ and $O_3$ from anthropogenic emissions ~73% and 37%, respectively. A similar study from Stockholm reported that $PM_{10}$ and $PM_{2.5}$ are associated with daily mortality (Meister, Johansson and Forsberg, 2012).

Where the evidence for the effect of PM has been comprehensively reviewed, e.g. by the United States Environmental Protection Agency, World Health Organisation or UK Committee on the Medical Effects of Air Pollution, there have been consistent conclusions that exposure to PM is associated with a range of negative health outcomes. The UK Committee on the Medical Effects of Air Pollutants reported the effects of long-term exposures to particulate air pollution was likely to affect cardiovascular morbidity in the UK (COMEAP, 2018). The British Heart Foundation reported that the mortality by cause from all heart and circulatory diseases in 2017 was 168,472 people in the UK, and for global mortality from cardiovascular disease in 2017 was estimated to 17,790,949 people (BHF, 2019). Additional studies indicated coherence between long-term PM exposure and the risk of premature mortality (Vodonos, Awad, and Schwartz, 2018; Pinault *et al.,* 2017; COMEAP, 2009). Another study in China between 2000 and 2010 found that $PM_{2.5}$ induced premature mortality up to 1,255,400 premature deaths in 2010, 42% higher than the level in 2000 (Xie, R. *et al.*, 2016).

The WHO Review of the Evidence of the Health Aspects of Air Pollution (REVIHAAP) conducted in 2013, concluded that, since the previous review, conducted by WHO in 2005 had been completed, a substantially larger number of studies had been conducted which provide support for 'the effects of short-term exposure to $PM_{2.5}$ on both mortality and morbidity, based on several multicity epidemiological studies', and 'the effects of long-term exposures to $PM_{2.5}$ on mortality and morbidity'. Key plausible biological mechanisms proposed for the effect of PM on human health include oxidative stress leading to inflammation (Kelly, 2003). When considering the effects of PM on human health, key questions include the role of different components of PM in driving the negative health outcomes, and the relative influence on repeated exposure to short-term

high concentration episodes. The WHO REVIHAAP review concludes that there is some evidence for a differential effect of different PM components on human health. REVIHAAP, 2013 concludes 'Epidemiological and toxicological studies have shown PM mass ($PM_{2.5}$ and $PM_{10}$) comprises fractions with varying types and degrees of health effects, suggesting a role for both the chemical composition (such as transition metals and combustion-derived primary and secondary organic particles) and physical properties (size, particle number and surface area', but concludes that the evidence is insufficient and the total PM mass is the most appropriate metric to evaluate health risks from PM. In addition, on the averaging period, REVIHAAP, 2013 concludes that there is a substantially larger health burden from long-term exposure (characterised by annual average concentrations) that is not simply the sum of short-term exposure (e.g. 24-hour average concentrations), and therefore that the annual average concentration represents the most important metric for evaluating health risks from PM exposure.

Thailand has only a few studies on human health impacts, a summary of Thai air quality literatures on health effects as shown in Table 1.1. Recent studies in Thailand from Phosri *et al.* (2019) reported that ambient air pollution from $O_3$, $NO_2$, $SO_2$, $PM_{10}$, and CO was associated with increasing risk of hospital admissions for cardiovascular and respiratory diseases in Bangkok, Thailand, the elderly people age ≥ 65 years seemed to be the most vulnerable group to the effect of these air pollutants. Another study from Pothirat *et al.* (2017) confirmed that the effects of seasonal smog associated with an increased $PM_{10}$ level on emergency visits for asthma and chronic obstructive pulmonary disease exacerbations in Chiang Mai, Thailand. Naksen *et al.* (2017) also showed the evidence that urinary 1- Hydroxypyrene level (a predominant biomarker of exposure to polycyclic aromatic hydrocarbons) during haze episode in northern Thailand among school children is higher than the previous report in other region of Thailand and other countries. Guo *et al.* (2014) studied the effects of exposure to $PM_{10}$, $SO_2$, and $O_3$ and the increased risk of mortality risks associated with an increase of 10 $\mu g\ m^{-3}$ in $PM_{10}$, 10 ppb in $O_3$, 1 ppb in $SO_2$ in three seasons during 1999–2008 in 18 provinces across Thailand. This study showed that $PM_{10}$ was significantly related to respiratory mortality, while $O_3$ was significantly associated with cardiovascular mortality and the effects of all pollutants were higher in summer and winter than in the rainy season on all mortality, for example, an increase of 10 $\mu g\ m^{-3}$ in $PM_{10}$ was associated with a 0.6%, 0.2% and 0.3% increase of respiratory mortality in summer, rainy season and winter, respectively. Whereas,

Buadong *et al.* (2009) reported that a short-term association between increased daily levels of $PM_{10}$ and $O_3$ and the number of daily emergency hospital visits for cardiovascular diseases, particularly among aged ≥ 65 years was observed in Bangkok, Thailand. A further study from Vichit-vadakan, Vajanapoom and Ostro (2008) on the mortality risk from air pollution in Bangkok, Thailand suggested strong associations between several different mortality outcomes and $PM_{10}$. Thus, from the previous studies mentioned above, the relationship between the conditions producing air pollutant concentrations in the atmosphere and the resultant health effects needs further investigation.

**Table 1.1:** Summarising the Thai air quality on health effects

| Health effects | Pollutants | Averaging | Reference |
|---|---|---|---|
| **Increasing risk of hospital admissions for cardiovascular and respiratory diseases on the elderly people age ≥ 65 years** | $O_3$, $NO_2$, $SO_2$, $PM_{10}$, CO | Long-term exposure (2006-2014) | Phosri *et al.* (2019) |
| **Increasing risk of emergency room visits for asthma and chronic obstructive pulmonary disease exacerbations** | $PM_{10}$ | Long-term exposure (2006-2009) | Pothirat *et al.* (2017) |
| **Increasing risk of all-cause mortality** | $PM_{10}$, $SO_2$, $O_3$ | Long-term exposure (1999–2008) | Guo *et al.* (2014) |
| **Increasing risk of daily emergency hospital visits for cardiovascular diseases, particularly among aged ≥ 65 years** | $PM_{10}$, $O_3$ | Long-term exposure (2002-2006) | Buadong *et al.* (2009) |
| **Increasing risk of all-cause mortality** | $PM_{10}$ | Long-term exposure (1999-2003 | Vichit-vadakan, Vajanapoom and Ostro (2008) |

In terms of the effect that PM has on human health, as stated above, there are different components of PM. The latest review of the evidence on health effects of air pollution conducted by the WHO in 2013 concluded that there is some evidence for different toxicity of some components of PM compared to others (WHO, 2013). However, they concluded that this evidence was not strong enough to differentiate effects on health between different PM components. Therefore, it was recommended that human health-relevant PM concentrations were quantified as the total PM mass. For this reason, total PM mass (both $PM_{10}$ and $PM_{2.5}$) are used here to quantify PM concentrations relevant for human health (WHO, 2013).

## Annual average metrics

In addition to the quantification of PM as the total mass concentration, another key consideration is what time-averaged metric to use when quantifying PM relevant for human health. Studies have shown associations between short-term (e.g. hourly) variation in PM concentrations and impacts on human health (e.g. decreased lung function in laboratory studies, increases in premature mortality in time series epidemiological studies). In addition, cohort studies that assess changes in health impacts across populations have shown strong associations between long-term exposure (quantified as the annual average metric) and negative health outcomes such as premature mortality. The WHO REVIHAAP (REVIHAAP, 2013) review concluded that acute and long-term effects are partly interrelated, the effects of long-term exposure are much greater than short-term exposure. However, the long-term effects are not the sum of all short-term effects.

As a result, the metrics used to quantify of long-term health-relevant PM from various studies are the annual average $PM_{10}$ and $PM_{2.5}$ concentrations (Anenberg *et al.*, 2018; Malley *et al.*, 2016; WHO, 2006). Advantages of using the annual average concentrations is that focusing on long-term exposure allows a more complete accounting for the effects of PM exposure on human health. WHO (2013) states that the health impacts from long-term exposure to PM are not simply the sum of the health impacts from short-term exposure, and therefore that long-term exposure to PM has an additional burden on human health. Therefore, by using annual average PM as the metric to quantify health impacts, a larger fraction of the totality of the burden of disease attributable to PM exposure can be quantified, compared to using short-term exposure metrics (e.g. daily PM concentrations).

The challenge for governments around the world is to improve air quality in their cities in order to protect human's health. Therefore, many countries have established their own national standards to control the emissions of pollutants following the Air Quality Guidelines from World Health Organization (WHO). For example, for PM in Thailand, standards were set at 50 μg $m^{-3}$ as an annual average concentration for $PM_{10}$ by the Pollution Control Department (PCD) (PCD, 2004) and 25 μg $m^{-3}$ as an annual average concentration for $PM_{2.5}$ (PCD, 2010a). The WHO Guidelines values are even more stringent, with annual mean $PM_{10}$ concentrations of 20 μg $m^{-3}$ and annual mean $PM_{2.5}$ set at 10 μg $m^{-3}$ (WHO, 2006) as presented in Table 1.2.

**Table 1.2:** Air quality guidelines by WHO and air quality standards in Thailand by PCD

| Air quality guidelines/Standards | WHO (2006) | | PCD (2010a) | PCD (2004) |
|---|---|---|---|---|
| | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ |
| Annual mean (μg $m^{-3}$) | 10 | 20 | 25 | 50 |

Due to the larger effect that long-term exposure has on human health, this thesis focusses on how annual average PM is derived from variation in short-term (i.e. hourly) PM variations. The interrelation between short-term peak PM concentrations, and long-term annual average concentrations is explored in Chapters 3 and 4 through analysis of PM monitoring data in Thailand.

## 1.5 Quantifying particulate matter

### 1.5.1 In situ measurements

Ground-based monitoring of PM at measurement stations allows accurate concentration of PM to be measured in-situ. A variety of measurement methods for monitoring at ground stations have been developed, including high-quality 'reference' monitors, to 'low cost' sensors that can be carried as a person undertakes daily activities (Lung *et al.*, 2018). The key advantage of ground-based measurement of PM is that sites can be located in different parts of a city, and outside the city to understand how PM varies in different locations. Long-term monitoring at a single site allows long-term trends to be assessed over time, e.g. to assess the effect of implementing policies to reduce PM (or to assess increasing trends due to socioeconomic development in the absence of policies to control emissions). Key considerations when developing a monitoring network are to ensure that the sites where PM is monitored are assessed in terms of their representativeness, and that gaps in the monitoring network for which the monitoring stations are not representative are identified.

Commonly, ground based monitoring networks are used to assess compliance with air quality standards, and to analyse long-term trends in PM concentrations. However, studies (Punsompong and Chantara, 2018; Field et al., 2016; PCD, 2015; Kim Oahn and Leelasakultum, 2011) have shown that in those regions where PM concentrations are highest, and therefore where risks to human health are most serious (i.e. in Africa and parts of south and south-east Asia), the number of PM measurement sites to monitor and quantify PM levels is lowest.

### 1.5.2 Remote sensing data

Remote sensing is a technology of observing the earth surface or the atmosphere by using electromagnetic spectrum/radiation without being in direct contact with the objects or areas (Bakker, et al., 2009; Blaschke, 2005; Dyring, 1973). This technique has been widely applied in mapping PM concentrations (Hua *et al.*, 2019; Li, Yang and Wang, 2015; Kloog *et al.*, 2014; Kloog *et al.*, 2011; Niemi et al., 2009) because the ground measurement networks still have a limitation to evaluate the spatial distribution and the

regional transport of PM (Engel-Cox *et al.*, 2004) , especially in the areas with inadequate air quality monitoring stations, the remote sensing, for example using satellite is an effective method to estimate air quality on a large scale (Li, Yang and Wang, 2015).

### 1.5.3 Modelling of air pollution

Modelling of air pollution concentrations involves first quantifying the strength of emissions that contribute to PM concentrations, and distributing those emissions based on where they are emitted. Next, the atmospheric transport and chemical reactions that different pollutants undergo in the atmosphere have to be modelled, to convert the emissions of a pollutant into the resulting PM concentrations in the geographic location that is of interest. As stated above, this process needs to take into account emissions emitted close to the area of interest, but also emissions emitted distant from this area, due to the effect that long-range transport can have on PM concentrations distant from the emission source. The modelling of air pollution concentrations can be undertaken with varying levels of complexity and completeness in terms of the representation of atmospheric processing on PM and PM precursor emissions. There are several different types of air quality models with different purposes such as dispersion models, photochemical models and receptor air quality models (U.S. EPA, 2019b). Dispersion models are used to estimate the concentration of pollutants surrounding emission sources at ground-level receptors (U.S. EPA, 2019b). Photochemical models are used to simulate the impacts from all sources by estimating pollutant concentrations and deposition of both inert and chemically reactive pollutants over a variety of spatial scales that range from urban to continental (U.S. EPA, 2010). Receptor models are observational techniques which use the chemical and physical characteristics of gases and particles measured at source and receptor to both identify the presence of and to quantify source contributions to receptor concentrations (U.S. EPA, 2019b) as shown in Table 1.3.

**Table 1.3:** Type of models for air pollution forecasting

| Type | Method | Reference |
|---|---|---|
| **Dispersion modelling** | - American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD)<br>- CALPUFF | U.S. EPA (2019b) (https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models) |
| **Photochemical modelling** | - Community Multiscale Air Quality (CMAQ): To simulate the numerous physical and chemical processes involved in the formation, transport, and destruction of particulate matter, ozone, and other air pollutants (U.S. EPA, 2010)<br>- Comprehensive Air Quality Model with Extensions (CAMx) Modelling | |
| **Receptor modelling** | - Chemical Mass Balance (CMB) Model<br>- Positive Matrix Factorization (PMF) | |

The advantage of modelling PM concentrations is that the magnitude of PM concentrations in a location can be directly linked to the emissions that produce this level of PM concentrations. This allows the major sources of PM concentrations to be identified, including the contribution from major source sectors, and different geographic regions. Finally, modelling of PM concentrations also facilitates assessment of how PM concentrations are likely to change into the future for different projections of emissions (driven, e.g. by different assumptions of socioeconomic development and/or implementation of different sets of policies and measures). This facilitates planning on how PM concentrations can be produced as the implementation of different policies and mitigation measures can be evaluated in terms of i) their effect on reducing PM and PM precursor emissions and ii) their effect on PM concentrations and impact on human health.

The air pollution modelling techniques listed above which model the emission, transport and chemical reaction of pollutants in the atmosphere typically require a supercomputer to run. The time and computational power required to run these models limits their application. One such atmospheric chemistry transport model is the GEOS-Chem model. GEOS-Chem is a 3D atmospheric chemistry transport model with 27 vertical layers in the atmosphere that accounts for the atmospheric transport and chemical reaction of pollutants in the atmosphere. It is a global model that can be run at various grid resolutions ranging

from 4x5$^{o}$ to smaller scale applications (0.25x0.31$^{o}$), and has also been applied regionally (Bey, 2001). The traditional running of the GEOS-Chem model is similar to other atmospheric chemistry transport models, which require substantial computing power to run. However, an additional application of GEOS-Chem, called the GEOS-Chem Adjoint model, provide the ability to more rapidly assess the consequences of changes in emissions on air quality in a particular location. The GEOS-Chem Adjoint model quantifies the sensitivity of changes in a particular metric (e.g. annual average $PM_{2.5}$ concentrations across Thailand) to changes in emissions of precursors in grid squares globally. The sensitivities can be combined with gridded emission estimates for different scenarios to estimate the effect of a particular emission changes on $PM_{2.5}$ exposure and health impacts. This GEOS-Chem Adjoint model can rapidly evaluate the effect of different changes in emissions, and was therefore used in this thesis to assess the effectiveness of different scenarios at reducing $PM_{2.5}$, as described in Chapter 2 and Chapter 5.

To effectively plans to reduce PM concentrations, a combination of monitoring networks measuring PM and modelling to assess sources and emission contributions have been utilised in different regions. The monitoring of PM allows historical and current PM concentrations to be determined (Punsompong and Chantara, 2018; Malley *et al.*, 2016; Querol *et al.*, 2009), and through statistical analysis, the different determinants of PM concentrations (e.g. long-range transport, source sectors etc.) to be explored. Long-term trends in PM data can be analysed using a fixed site monitoring network. Complementing monitoring network data with modelling of PM emissions and concentrations allows future changes in PM emissions to be explored, and the effect of different policies and measures to be analysed in terms of their effect on PM concentrations. This combination of monitoring and modelling has been used in different countries to plan for reductions in PM concentrations (and improvements in human health), particularly in Europe and North America, but also recently in China, and other developing countries. Moreover, the combination of statistical analysis of PM monitoring data and modelling of PM emissions and concentrations in Thailand can increase understanding of the drivers of PM concentrations in Thailand, and the most effective strategies for mitigation.

## 1.5.4 Emissions

Atmospheric emissions are one of the most important contaminants emitted into the atmosphere from the diffuse pollution (Matthias *et al.,* 2018). Estimates of air pollutant emissions are essential to understand the contribution of different sources to $PM_{2.5}$ concentrations, and to use as input into atmospheric chemistry transport modelling. The general approach and terminology associated with estimating emissions is shown in Table 1.4. In general terms, the estimation of emissions can be based on the equation (U.S. EPA, 2017):

$$E = A \times EF \times (1-ER/100)$$

*Where:*

| | | |
|---|---|---|
| E | = | Emissions |
| A | = | Activity Rate |
| EF | = | Emission Factor |
| ER | = | Overall emission reduction efficiency (%) |

Comprehensive guidance has been developed for estimating air pollutant emissions from different sources (EMEP/EEA 2019). These guidance documents provide methods by which the general equation above is translated into specific methodologies to estimate emissions from major air pollution emitting source sectors. For example, the EMEP/EEA (2019) air pollution emission inventory guidebook describes the activity data that can be used to quantify the emissions from each source sector. This varies the from the fuel consumed in energy industries, to the total number of vehicle-km travelled by a particular type of vehicle (the activity data used to quantify emissions for each sector are further described in Chapter 5 of this thesis). The EMEP/EEA (2019) emission inventory guidebook also provides default emission factors (in units of kg pollutant per unit of activity) that can be used in combination with the activity data to estimate emissions from a particular source.

Key to the development of emission inventories is the concept of 'tiers' of methodologies. Within the EMEP/EEA (2019) emission inventory guidebook, three tiers of methodologies are outlined that provide the basis for quantifying emissions from particular sources. 'Tier 1' approaches are the simplest methods that can be used to

quantify emissions using only default data and assumptions. ‘Tier 2’ approaches are more detailed, and may require some country-specific data to be able to estimate emissions, while the most complex methods, ‘Tier 3’, are based solely on country-specific data. The ability to quantify emissions using methods with different levels of complexity, data requires and specificity has the advantages of i) allowing countries that have limited data to still estimate air pollutant emissions, ii) allowing prioritisation of key sources using the more complex methods, while still being comprehensive by estimating emissions from minor sources using Tier 1 approaches, and iii) allowing emission inventories to be gradually improved a new data becomes available. In this thesis (Chapter 5), a range of methods are used to quantify emissions from different sources in Thailand.

**Table 1.4:** Components of emission models

| Terminology | Definition | Reference |
|---|---|---|
| **Emissions** | Flux of a substance X entering the atmosphere/ An emission rate is an amount of emission per unit time (e.g., kilograms of PM per year). | Matthias et al. (2018), NARSTO (2005) |
| **Emission inventory** | A database that lists, by source, the amount of air pollutants discharged into the atmosphere during a year or other time period (units of weight, volume, distance and etc.)/ A critical foundation of air quality management activities. | U.S. EPA (2019b), NARSTO (2005) |
| **Activity** Rate | A measure of the driving force for the operation that produces emissions (e.g., kilograms of fuel burned per month or time period of interest)/Quantity describing the activity relevant for the emissions of a certain source ( e.g., amount of fuel used, distance travelled, or amount of energy converted) | Matthias et al. (2018), NARSTO (2005) |
| **Emission Factor** | A numerical value that attempts to relate to the quantity of a pollutant emitted to the atmosphere with an activity associated with the release of that pollutant (weight of pollutant emitted divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant) | U.S. EPA (1997), U.S. EPA (2007) |
| ER | The product of the control device destruction or removal efficiency and the capture efficiency of the control system. | U.S. EPA, 1997 |
| **GEOS-CHEM** | 'A global 3-D model of atmospheric chemistry driven by meteorological input from the Goddard Earth Observing System (GEOS) of the NASA Global Modelling and Assimilation Office' | http://www.geos-chem.org |

# 1.6 Background of Thailand

The Kingdom of Thailand (Thailand) is located at the heart of the Southeast Asian mainland, covering an area of 513,115 square kilometres; 1,620 kilometres from North to South and 775 kilometres from East to West. With a population of 69.4 million, it is the world's 20th largest country, and the fourth largest nation in ASEAN (Association of Southeast Asian Nations) after Indonesia, the Philippines and Vietnam (World Bank, 2019) as shown in Figure 1.5.


**Figure 1.5:** Map of Thailand (Nations online, 2019)

Bangkok is the capital city of Thailand. The population in Bangkok in 2018 was 5.7 million people (Department of Provincial Administration, 2018). Major cities are Chiang Mai (North), Songkhla (South), Ayutthaya and Chonburi (Central Plains), Nakhon Ratchasima and Khon Kaen (Northeast). Thailand has a tropical climate, with a hot and humid climate throughout the year. The climate of Thailand is also under the influence of monsoon winds of seasonal character such as the Southwest monsoon and Northeast monsoon. The Southwest monsoon which starts in May brings a stream of warm moist air from the Indian Ocean towards Thailand causing abundant rain over the country. The Northeast monsoon starts in October brings the cold and dry air from the anticyclone in China mainland over major parts of Thailand, especially the Northern and Northeastern Parts. In the Southern Part, this monsoon causes mild weather and abundant rain along the eastern coast (Meteorological Department, Thailand, 2016). The seasonal weather patterns affect concentrations and dispersions of ambient air pollution, with concentrations and dispersion of air pollutants in the wet season being less than in the dry season (PCD, 2015).

## 1.7 State of air quality in Thailand

The Pollution Control Department (PCD) under the Ministry of Natural Resources and Environment, Thailand, has the responsibility for preventing and controlling air pollution under the Enhancement and Conservation of National Environmental Quality Act (1992). The PCD has reported the state of air quality in Thailand for 2018, which has improved over the last few years as a result of the success of pollution management by the relevant Thailand government agencies. However, ambient air quality from 63 general monitoring stations across Thailand stills exceeded the standard for $PM_{2.5}$ and $PM_{10}$ as shown in Table 1.5 and Figure 1.6 (PCD, 2019).

**Table 1.5:** The national 24 hours and annual average PM concentrations all sites across Thailand

| **PM Standard (µg $m^{-3}$)** | | | **Air quality in 2018 (µg $m^{-3}$)** | |
|---|---|---|---|---|
| **Standard** | **$PM_{2.5}$** | **$PM_{10}$** | **$PM_{2.5}$** | **$PM_{10}$** |
| 24 hours average | 50 | 120 | 3 - 133 | 2 - 303 |
| Annual average | 25 | 50 | 9 - 41 | 23 - 120 |

Figure 1.6 (a) shows the percentage of days from all pollutants were not exceeded the 24-hours average standards in 7 provinces in Thailand mainly occurred in Southern Thailand (Blue colour). However, the highest percentage of days exceed the standards occurred more than 20% in central sites (Including Bangkok) from 4 provinces (Red colour). Figure 1.6 (b) shows the trends of annual average from different air pollutants from 2008 to 2018 were steady except $PM_{2.5}$, Ozone, and $PM_{10}$ still exceed the standards.

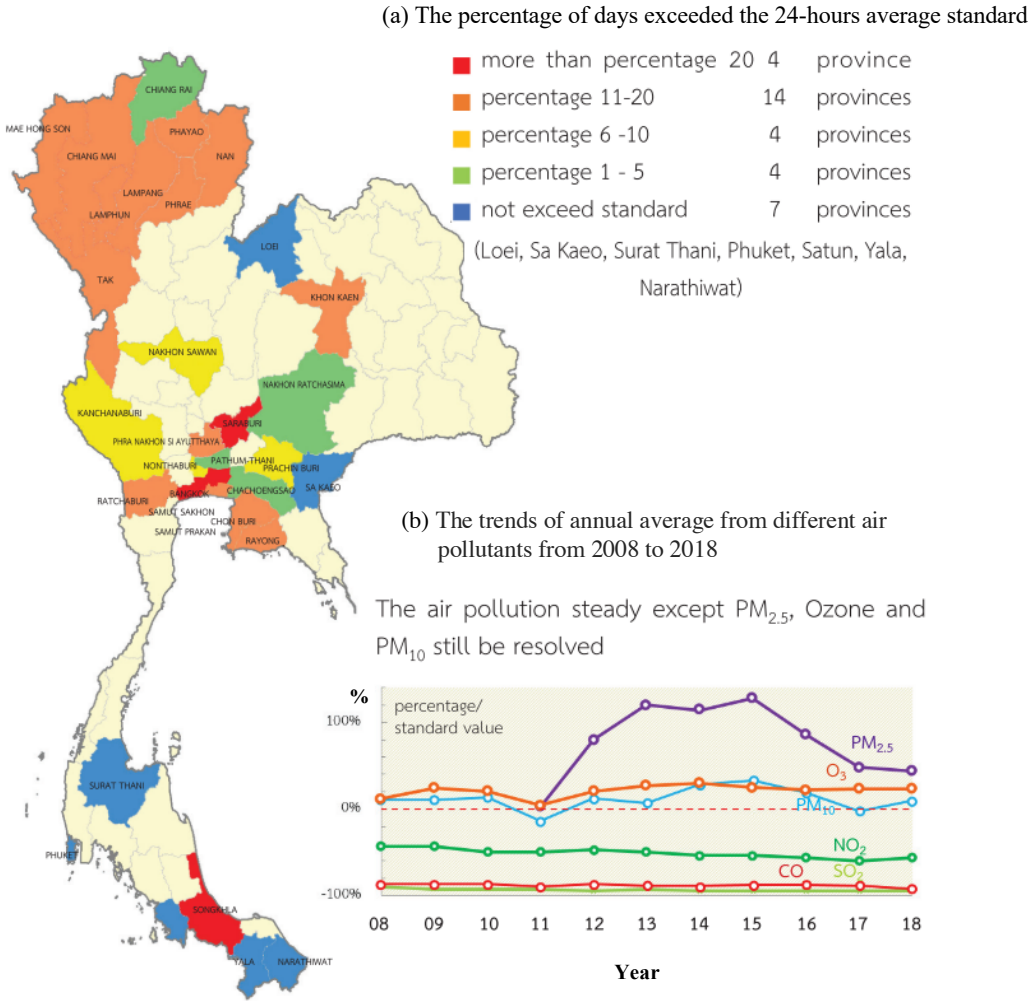



**Figure 1.6:** The state of air quality across Thailand in 2018 (a) The percentage of days exceeded the 24-hours average standards (b) The trends of annual average from different air pollutants from 2008 to 2018 compared to the standards (PCD, 2019)

The state of air pollution in critical areas of Thailand in 2018 (PCD, 2019) was 1) In Northern Thailand there was a haze problem caused by open burnings and forest fires. The situation has improved by decreasing the number of days with particulate matter and the hotspots accumulation that exceeded the standards. 2) Bangkok Metropolitan Region (BMR) (including the capital city and five adjacent provinces), the main source is from the vehicles, $PM_{2.5}$ concentrations were also accumulated in the atmosphere due to the meteorological conditions with no wind and air circulation, and 3) In the Na Phra Lan Subdistrict, Saraburi province, the major sources are a diffusion of particulate matter from cement plants, lime plants, stone crushing plants, quarries in the area and nearby as well as traffic congestion transportation and logistics activity in the area where roads are damaged). The Thailand PCD has stated that all these problems need to be solved with intensive mitigation measures (PCD, 2019).

In 2019, PCD reorganised its air quality management plans by cooperating with the Asian Institute of Technology (AIT) to study and update the sources of $PM_{2.5}$, $PM_{10}$, CO, $SO_2$, NOx, HC, $CO_2$ from transportation, industry, residences, commercial buildings, open-burning, forest fires, waste, agriculture, as well as fugitive emission sources. AIT was then tasked to develop a $PM_{2.5}$ source database, including activities and pollution emissions in BMR during November and February, because this period tends to have high $PM_{2.5}$ concentrations every year. With this new project the PCD was able to make plans to deal with the smog and dust problems each year (PCD, 2019).

The PCD, Department of Health and EHT under the leadership of the Chulabhorn Research Institute and the United Nations Environment Programme (UNEP) have established a project on Air Quality Assessment for Health and Environment Policies in Thailand (UNEP supported the budget) in order to evaluate the situation and collect academic data for policy recommendations on air quality management and health impacts. The plan was that the project would be beneficial to the operation, preparation and improvement of air quality management measures / standards in Thailand by linking to the health impact data, economy and society. The results showed that the rate of illness caused by the relationship between air pollution concentration of $PM_{2.5}$, $PM_{10}$, $O_3$ in the study areas (namely, Hat Yai District, Songkhla Province, Na Phralan Subdistrict, Chaloem Phra Kiat District, Saraburi Province and Muang District, Chiang Mai Province) correlates with the number of patients with respiratory diseases, lung cancer and coronary artery disease. The study looked at the relationship between numbers of citizens and air

pollution impacts, and determined that each province has a different risk rate of exposure to air pollution. The project also showed the risks for different age groups, for example, populations older than 60 years should be aware of the impact on air pollution more than the normal population, etc. (PCD, 2019).

Another cooperation on air quality management and health impacts, is that the PCD has signed a memorandum of cooperation on environmental health and toxicology with the Department of Health, Ministry of Public Health and Center of Excellence on Environmental Health and Toxicology (EHT) (August 15, 2019). The objectives were to support research studies, develop and increase the capability of personnel and operators, develop policies/measures and exchange information on health, toxicology and environmental operations, including promoting the role of Thailand in the international cooperation forum for hygiene toxicology and environment (PCD, 2019).

## Research on PM from Thailand

Several studies in Thailand have demonstrated various sources of air pollutants. In Bangkok, the major contributor to $PM_{10}$ and $PM_{2.5}$ was from traffic (mobile sources and road dust) in both wet and dry seasons (Kim Oanh et al., 2006; Loetkamonwit, 2000). During the intensive burning season (November-April) smoke plumes from rice straw burning in Pathumthani (the intensive burning area of the Bangkok Metropolitan Region (BMR)) can be transported to Bangkok following the Northeast monsoon while higher numbers of hotspots were observed during the rice straw burning period (from November to April next year) (Tipayarom and Kim Oanh, 2007). Air pollution levels during the dry months in Bangkok are much higher than the wet months (Kim Oahn et al., 2006). Chuersuwan et al. (2008) studied the major sources of $PM_{10}$ and $PM_{2.5}$ in BMR at four monitoring stations. The major source of $PM_{10}$ and $PM_{2.5}$ at traffic sites indicated the importance of automobile emissions and biomass burning as sources of PM. However, biomass burning was the major source of $PM_{2.5}$ at residential sites as well. Other studies of PM concentrations at three Bangkok mass transit system (BTS) stations showed the PM concentrations were increasing with the traffic volume under BTS stations whilst with increasing height, PM levels were decreased (Lertphuthipisut, 2004).

Emissions from biomass burning (from forest fires and from the burning of agricultural crop residues) are major sources of PM in Thailand, and contribute to regional/long-range

transport. Studies (Field et al., 2016; Betha, Behera and Balasubramanian, 2014; Kim Oahn and Leelasakultum, 2011) have also reported the impact on short-term peaks in PM concentrations in Thailand and the contribution from neighbouring countries to these 'haze' episodes resulting from intense biomass burning episodes. For example, in Northern Thailand, most areas are mountainous, which are largely covered by forest and agricultural lands, and biomass open burning is a very important seasonal source of air pollution there. This is especially the case in Chiang Mai province, with frequent forest fires during the dry season, 78% of the area is covered by forest and the burned forest area for the whole Northern region during 2004–2008 was the highest in 2004 (107 $km^2$) (MONRE, 2007). Haze episodes in Northern Thailand typically occur from forest fires and agricultural open burning both locally (i.e. within Thailand) and through transboundary transport from neighbouring countries, which only occurs during the beginning of the year between January and April (PCD, 2015). Kim Oahn and Leelasakultum (2011), identified the highest 24-hr $PM_{10}$ concentrations and 95$^{th}$ percentile value were 396 μg $m^{-3}$ and 234 μg $m^{-3}$ in Chiang Mai occurred during March in 2007, and air mass back trajectories on haze episode days had passed over regions of dense biomass fire hotspots before arriving in Chiang Mai.

Other research (Punsompong and Chantara, 2018; Phayungwiwatthanakoon, 2013; Ruanngern, 2012; Kim Oahn and Leelasakultum, 2011) on open burning emissions in Northern Thailand, estimate that the annual emission averages are as follows: annual emission estimation for 2010 from open burning in Prayao, Northern Thailand was 21,554 ton for $PM_{2.5}$, and 43,577 ton for $PM_{10}$. Open burning is mostly found in forest (93%) and biomass is frequently burnt in March, April and February (Ruanngern, 2012). In southern Thailand, $PM_{10}$ concentration tends to increase during July to October due to forest fires in Sumatra (PCD, 2015). Borneo and Indonesia also faces the least pollution problems (Field et al., 2016). Moreover, during the rainy season when compared to other regions in Thailand, air flows and air pressure circulated the air into the higher atmosphere, resulting in pollutants being less concentrated at the source (Field et al., 2016; PCD, 2015).

Punsompong and Chantara (2018) showed for one monitoring site in Chiang Mai in northern Thailand between 2010 and 2015 that high $PM_{10}$ concentrations mainly occurred in dry season during February to April. Based on potential source contribution function analysis of air mass back trajectories, they estimated that during this period the contribution to hourly $PM_{10}$ concentrations from Myanmar was 73% and from Thailand

was 27%. In Myanmar, the major high-potential sources were open agricultural burning, followed by forest burning, and in Thailand, the major contribution was from agricultural burning. Other previous studies have also highlighted the role of biomass burning in northern Thailand, Myanmar, and other Southeast Asian countries to short-term peaks in $PM_{10}$ concentrations (Kim Oahn and Leelasakultum, 2011; Phayungwiwatthanakoon, 2013; PCD, 2010b; PCD, 2012).

In summary, previous research has shown that biomass burning makes a substantial contribution to high PM concentrations in Northern Thailand during specific parts of the year, i.e. it contributes to short-term peak PM concentrations. However, none of these studies have assessed the effect that these episodes have on overall annual average PM concentrations across Thailand.

Several studies in Thailand have demonstrated that exposure to PM is associated with an increased risk of adverse health effects. Premature deaths in Thailand related to air pollution were estimated to have increased by 74% from 21,651 to 37,577 between 1995 and 2015 (GBD, 2015). Studies on health effects of $PM_{10}$ on the lung function of a policemen group from a heavy traffic area in Bangkok and a control group from Ayutthaya province, found that the 24-hr average concentration of $PM_{10}$ in Bangkok was three times higher than the rural area control (Boudoung, 1999). Lung function of the group in Bangkok was significantly lower than the control group ($P<0.05$) (Boudoung, 1999). Health effects of indoor respirable particulates have also been reported among housewives and children in the inner Bangkok area, suburban area, and Amphoe Phimai Nakornratchasima province (Subsuk, 2000). The study revealed that the symptoms of respiratory disease, of non-specific respiratory disease and persistent cough and phlegm indicated that suburban area was better for health than the Amphoe Phimai Nakornratchasima and the inner Bangkok area (Subsuk, 2000). The exposure levels of drivers to $PM_{2.5}$ and $PM_{10-2.5}$ (Particulate Matter with an aerodynamic diameter of wider than 2.5 and less than 10 microns) on four bus routes in Bangkok found that the PM exposure level was higher than in the general environment and it varied with the seasons and vehicle type. The major component of PM was carbon, derived from different vehicle types exhausts; air-conditioned bus, non-air-conditioned bus, tuk-tuk and taxi. The implication was that exposure to $PM_{2.5}$ in public transportation vehicles could have harmful health effects on both drivers and commuters, where air pollution from vehicle exhaust is a serious problem (Jinsart et al., 2012).

## 1.8 Thailand research gaps

There is a considerable gap in knowledge of air pollution variation based on previous studies conducted in Thailand. Many research studies have focused on the contribution of PM into the atmosphere from different sources and periods. However, as summarised above, the studies that have been conducted on PM concentrations in Thailand have not explicitly assessed the contribution of biomass burning, and other seasonal sources of air pollution to the magnitude of the *annual average* PM concentration. This is important because it is the annual average concentration that is most strongly associated with negative health effects, as a proxy for long-term exposure to PM (as opposed to hourly or daily PM concentrations, which characterise short-term exposure). Thailand has an annual average standard for $PM_{10}$ and $PM_{2.5}$ concentrations, against which monitored PM concentrations are assessed for compliance with these standards in different regions. However, the Pollution Control Department only assesses compliance with these standards. There is substantial potential to utilise the monitoring data collected by PCD through additional statistical analysis to identify the variation in hourly PM concentrations that produce a particular magnitude of annual PM concentrations at a particular site, and through this analysis to gain insight into the drivers (including the contribution of long-range transport vs local emission sources and the contribution of different emission source sectors) that produce annual PM concentrations at different monitoring sites.

A statistical framework for analysing air pollution monitoring data, called chemical climatology, has been applied in the UK, and to assess PM concentrations in other European cities (Malley et al., 2016; Malley, Braban, and Heal, 2014). The ‘chemical climatology’ framework consists of three components that defines as ‘the impact, ‘the state’, and ‘the drivers’. The ‘impact’ is an identified effect of atmospheric composition from sources and processes which are associated with different chemical climates. The ‘state’ represents ‘what’, ‘when’ and ‘where’ of atmospheric composition producing the identified impact. The ‘drivers’ are the sources and influences on the atmospheric composition that determine the state, and the impact (Malley, Braban, and Heal, 2014), for more details are shown in Chapter 2. This framework has not been applied in other regions, and not in areas where variation in PM concentrations, and their drivers, may be substantially different than in Europe, such as in south east Asia. Therefore, the

monitoring network data collected by PCD provides an opportunity to i) assess the utility of applying this framework in a south-Asian country, and ii) to investigate how PM concentrations most relevant for human health impacts (characterised by annual average concentrations) are produced in Thailand.

Therefore, an aim of this thesis is to apply this chemical climatology framework to Thailand's PM monitoring network. This involves development and consistently calculating a standard set of statistics at all sites in the network. The aim in calculating these statistics is to assess i) spatial variation in the magnitude of annual average PM across Thailand, ii) how variation in hourly PM concentrations (e.g. contribution from high, moderate and low hourly PM concentrations, and hourly PM concentrations occurring in different times of the year and day) contribute to annual PM concentrations and iii) to link this to the contribution of specific drivers of variation in PM concentrations, such as the contribution of different emission source sectors, and the contribution from local vs long-range transport.

The second major research gap is a lack of technical capacity within the Thai government to model the effect of different policies and measures on PM concentrations across Thailand. Studies (PCD, 2019; DLT, 2010-2017; DEDE, 2010-2017) have shown the effect of implementing particular policies in one sector, e.g. the effect of policies on the transport sector in Bangkok and assessed the magnitude of emissions coming from different sources. However, Thailand and its government have numerous programmes, plans, strategies and policies in different sectors that will affect the progression of PM and PM precursor emissions into the future (PCD, 2019; DLT, 2010-2017; DEDE, 2010-2017). These includes plans for climate change mitigation, to achieve the sustainable development goals, on renewable energy and energy efficiency, as well as those plans specifically designed to combat air pollution. The overall effect of Thailand's current plans to reduce air pollution have not been evaluated in terms of their likely effect on reducing PM and PM precursor emissions, and PM concentrations. This limits Thailand's ability to understand whether proposed actions are sufficient to achieve its air quality goals (e.g. compliance with the Thai national standard and/or WHO air quality guidelines), and to identify what additional actions would be needed to improve air quality further. Therefore, to address this second research gap, an integrated assessment modelling approach was used to model i) current emissions of PM and PM precursor emissions in Thailand, ii) projections of emissions into the future, and iii) changes in

annual average $PM_{2.5}$ concentrations across Thailand resulting from emission projections representing Thailand implementing its existing policies and additional actions taken to improve air quality.

The aim of this modelling component of this thesis is to assess how the current levels of annual average PM, captured by analysis of the monitoring data, are likely to change into the future, and to show where actions needs to be focussed in terms of specific source sectors, mitigation measures, countries (i.e. Thailand vs neighbouring countries) in order to reduce annual average PM concentrations below those levels that are currently measured.

# 1.9 Chapter Outline

This study is organised as a series of chapters (1 to 6), the content of each is described briefly below in relation to the aims of the study.

**Chapter 2:** Methodology

Following the introduction of Chapter 1, this chapter describes the methodology that was used to assess the conditions producing the annual average $PM_{10}$ concentrations at monitoring stations (general and roadside sites) across Thailand. This method uses a 'chemical climatology' framework which applies the HYSPLIT model to simulate air mass back trajectories. This chapter also describes a tool called the Long-Range Energy Alternatives Planning-Integrated Benefits Calculator (LEAP-IBC) which is used in Chapter 5 to evaluate emission inventories, $PM_{2.5}$ concentrations and associated health impacts both for the current day and 2030.

**Chapter 3:** Assessment of the contribution of long-range transport to annual $PM_{10}$ concentrations in Thailand

The third chapter focuses on the conditions producing annual average $PM_{10}$ concentrations at general monitoring sites in Northern and Southern Thailand, by applying the 'chemical climatology' framework to access the contribution of hourly $PM_{10}$ concentrations to the annual average and using back trajectory analysis to: assess the proportion of time air masses spend over different countries; when different hourly $PM_{10}$ concentrations occur; and to explore the relative contribution of long-range transport and local emission sources from biomass burning to annual $PM_{10}$ concentrations at these sites.

**Chapter 4:** Assessment of conditions producing annual average $PM_{10}$ concentrations at general and roadside sites in Bangkok and central Thailand

The fourth chapter focuses on the conditions producing annual average $PM_{10}$ concentrations at general and roadside monitoring sites in Bangkok and general sites in central Thailand, by applying the same methods as in Chapter 3 as mentioned above. The aim of this analysis is to understand the variation of hourly $PM_{10}$ concentrations, and their effect on annual average $PM_{10}$ concentrations as determined by local emission sources such as transport, industry, and long-range transport.

**Chapter 5:** Sources of $PM_{2.5}$ relevant emissions, atmospheric concentrations and strategies for the mitigation of health impacts in Thailand: A modelling study for 2010 to 2030

The fifth chapter applies the LEAP-IBC tool in Thailand to develop an emission inventory of all relevant air pollutants contributing to $PM_{2.5}$ concentrations and the potential health impact in historical years (2010-2017), and to estimate a baseline scenario projection towards 2030. LEAP-IBC is used to develop mitigation scenarios that model the implementation of different mitigation measures to improve air quality in Thailand projected into the future to 2030 in order to protect human health.

**Chapter 6:** Concluding Discussion and Implications for Thailand's Air Quality Policy

The final chapter summarises key results and implications from this thesis to understand the influence of emissions and associated meteorology on PM concentrations for a variety of geographical scales (i.e. from specific types of location, though national to transboundary scales to understand what influences air pollution from within and outside of Thailand. The existing mitigation and additional mitigation are assessed to see how effectively they meet the air quality standards and recommendations for future work are made.

# Chapter 2: Methodology

Chapter 1 outlined the research aims of this study as being to assess the conditions that are producing the annual average $PM_{10}$ concentrations across Thailand, historically, and into the future. This aim will be achieved through the statistical analysis of ground-based $PM_{10}$ measurements, and through modelling of current and future $PM_{2.5}$ concentrations. As stated in Chapter 1, the use of measurement and modelling aims to identify the contribution of key drivers of PM in Thailand, including long-range transport vs local emissions sources, and key source sectors such as biomass burning. The modelling approach allows the impact of the implementation of mitigation measures in the future to be assessed, as well as identifying the sources and drivers of annual PM concentrations that is also assessed through the measurement analysis.

The aim of this Chapter is to provide detailed description of the measurement and modelling approaches used to investigate the research aims of this thesis. This includes the measurement and data analysis approach used, and the overarching modelling methodology used. Specific information about the data and methods used are then expanded upon in the Methodology sections of Chapters 3, 4, and 5.

The two sub-sections of this chapter describe the process that was used to assess the conditions producing the annual average $PM_{10}$ concentrations at 64 monitoring stations across Thailand, i.e. the statistical analysis undertaken to quantify the impact, state, and drivers producing health-relevant PM in Thailand, and the modelling of emissions and impacts of $PM_{2.5}$ in historical years and into the future. Specifically, Section 2.1 describes $PM_{10}$ monitoring data that was used for data analysis and the criteria used to select the monitoring sites with the greatest data capture, and therefore where analysis was predominantly focussed (the application of the HYSPLIT model to simulate air mass back trajectories and statistics that were calculated at each site from the hourly $PM_{10}$ measurements and air mass back trajectory data), including describes the chemical climatology framework. Finally, Section 2.2 describes emissions, transport and impact scenario tool use of PM Modelling Framework (LEAP-IBC model).

## 2.1 PM Monitoring Data

To understand the magnitude of human health-relevant PM concentrations across Thailand, their variation and their drivers in historical year, the primary data used to assess this was hourly measured $PM_{10}$ concentrations measured between 2011 and 2015 at 64 locations across Thailand. The measurements made at these sites form part of the Thailand's official national air quality monitoring network, that was established, run and maintained by the Thai Pollution Control Department. The network was established in 1996 with 38 sites (PCD, 1995), and has gradually expanding to increase coverage in terms of regional representative across Thailand, as well as the types of locations where air pollutants are monitored (general, roadside, industrial etc.). The primary purpose of the monitoring network is to assess compliance with the Thailand National Air Quality Standards (PCD, 1995; PCD, 2004; PCD, 2007; PCD, 2009; PCD, 2010a). Therefore, in addition to monitoring $PM_{10}$, a range of other 'criteria' air pollutants are measured at the sites to compare against the Thai air quality standards. In this thesis, hourly $PM_{10}$ data were analysed because it is the metric for particulate matter that is most widely monitored across Thailand's national air quality network (in comparison to $PM_{2.5}$), and because particulate matter is the pollutant most closely associated with negative human health impacts. Data was analysed for 2011-2015 as they were the most recent years for which data was available, and selecting 5 years allowed inter-annual variability to be assessed. The following sub-sections provide further information regarding the composition of Thailand Air Quality Monitoring Network, and the measurement instruments and data processing undertaken to produce the raw hourly measurement data used in this thesis.

### 2.1.1 PM Measurement Network

Thailand has established an ambient air quality monitoring network to monitor main atmospheric pollutants in 1996. As of 2015, there were 64 monitoring sites operating across the network, measuring a range of air pollutants for which Thailand has established ambient air quality standards (PCD, 2015). These pollutants include $PM_{2.5}$, $PM_{10}$, TSP, $NO_2$, $SO_2$, CO, $O_3$, Lead (Pb) and VOCs across the country as shown in Table 2.1 (PCD, 2019). Under the Enhancement and Conservation of National Environmental Quality Act of 1992, the Pollution Control Department (PCD) is responsible for monitoring air quality in Thailand and preparing an annual report on the state of air quality of the country and

relevant report (PCD, 1995). The air quality monitoring network set up by the PCD aims to prevent and solve the air pollution problems in the country, and to reduce the negative effect on the public health and the economy. Table 2.1 shows, for each province in Thailand, the number of monitoring sites and the pollutants measured at each site (PCD, 2015).

**Table 2.1:** Measurement air pollutants by PCD in different regions across Thailand (PCD, 2015)

| Region | Number of Monitoring sites in 2015 (latest year considered in this study) | Pollutant Measurement in 2015 |
|---|---|---|
| **Bangkok** | 17 | $PM_{2.5}$, $PM_{10}$, TSP, $NO_2$, $SO_2$, CO, $O_3$ and Pb |
| **Central** | 14 | $PM_{2.5}$, $PM_{10}$, TSP, $NO_2$, $SO_2$, CO, $O_3$ and Pb |
| **North** | 14 | $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, CO and $O_3$ |
| **Northeast** | 3 | $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, CO and $O_3$ |
| **East** | 11 | $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, CO, $O_3$ and VOCs |
| **South** | 5 | $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, CO and $O_3$ |
| **Total** | **64** | |

**Remark:** There are 63 Monitoring sites in 2019 (PCD, 2019)

### 2.1.1.1 History of ambient air quality monitoring network in Thailand

A history and timeline for national ambient air quality monitoring network are shown in Figure 2.1 (PCD, 2019). In 1981, the National Primary Ambient Air Quality Standards were promulgated and subsequently revised in 1995, 2001, 2004, 2007 and 2010a). Then, in 1983, the first air quality monitoring system was installed 8 stations in Bangkok (not online system), after that in 1987, the first online and realtime continuous air quality monitoring system was installed 5 stations in Samut Prakarn, central Thailand with support from Japan International Cooperation Agency (JICA). In 1991, the third monitoring system (an online and realtime continuous system) 4 stations on the roadsides of streets in Bangkok. In 1992, PCD with the technical assistance from the Swedish Government started preparing the design of a nationwide ambient air quality monitoring network and a meteorological monitoring network. Finally, from 1996 onwards to present, the networks are gradually put in several phases through the upgrade of the existing air quality monitoring stations and the installation of new monitoring stations. The monitoring network currently consists of 63 monitoring sites across the country from 33 provinces (PCD, 2019) (see Table 2.1).

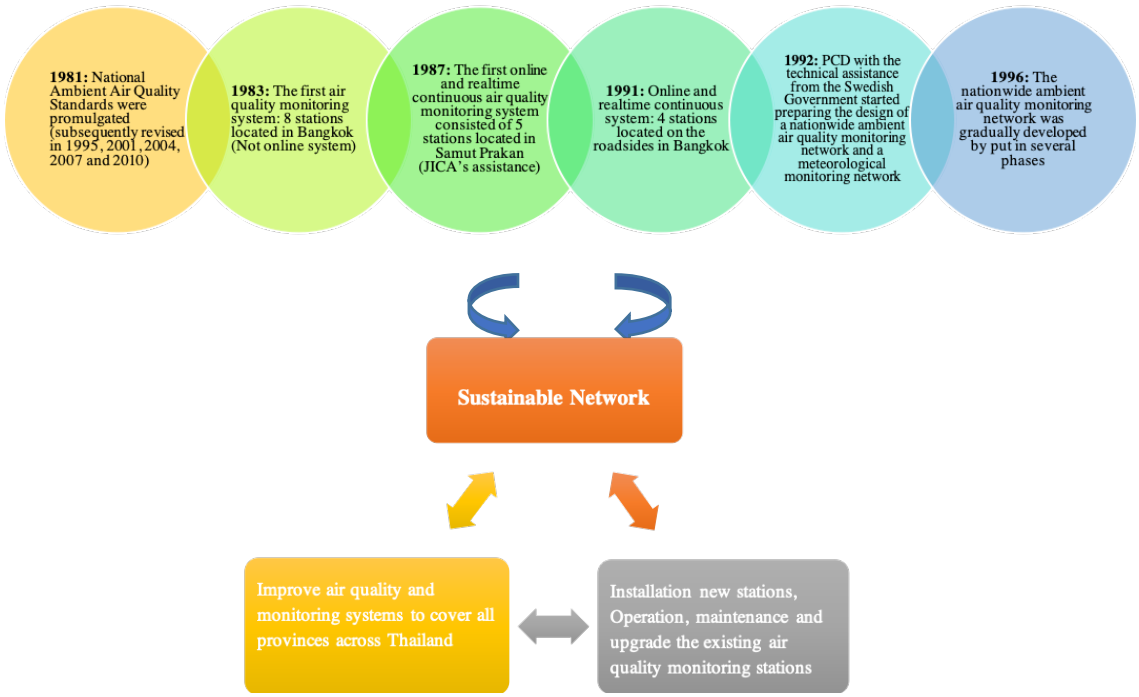



**Figure 2.1:** History and timeline of ambient air quality monitoring in Thailand (PCD, 2019)

### 2.1.1.2 Measurement instruments and methods

Monitoring and measuring air quality by PCD are carried out by a variety of different methods with continuous analysers and instruments as shown in Table 2.2 (PCD, 1995; PCD, 2004; PCD, 2007; PCD, 2009; PCD, 2010a). Monitoring methods used to measure particulate matter ($PM_{2.5}$, $PM_{10}$, TSP) concentrations follow the United State EPA reference methods or equivalent. $PM_{2.5}$, and $PM_{10}$ are measured using Beta Ray Attenuation principle (PCD, 2010a; PCD, 2004). $NO_2$ is measured using chemiluminescence detection, $SO_2$ is measured using UV Fluorescence/Pararosaniline, CO is measured using non-dispersive infrared detection, $O_3$ is measured using Chemiluminescence reaction, VOCs is measured using U.S. EPA Compendium Method TO-15, and Pb is measured using Atomic Absorption Spectrophotometry.

**Table 2.2:** Measurement methods of air pollutants

| Pollutants | Measurement Method at Thai National Air Quality Monitoring Network | Source |
|---|---|---|
| **$PM_{2.5}$** | Beta Ray Attenuation | PCD (2010a) |
| **$PM_{10}$** | Beta Ray Attenuation | PCD (2004) |
| **TSP** | Gravimetric High volume | PCD (1995), PCD (2004) |
| **$NO_2$** | Chemiluminescence | PCD (1995), PCD (2007), PCD (2009) |
| **$SO_2$** | UV Fluorescence/Pararosaniline | PCD (1995), PCD (2004) |
| **CO** | Non-dispersive IR | PCD (1995) |
| **$O_3$** | Chemiluminescence | PCD (1995), PCD (2007) |
| **VOCs** | U.S. EPA Compendium Method TO-15 | PCD (2009) |
| **Pb** | Atomic Absorption Spectrophotometry | PCD (1995) |

At each monitoring site, the inlet of instruments for gas analysers is placed at least 3 metres above ground level but not more than 6 meters, but for PM is placed at least 1.5 metres above ground level but not more than 6 meters (PCD, 1995; PCD, 2010a). In addition to monitoring atmospheric composition at each monitoring site, meteorological parameters including wind speed (WS) and wind direction (WD) are measured at 10 metres above ground level by cup propeller and potentiometer wind vanes; temperature (T), Barometric Pressure (BP) and relative humidity (RH) are measured at 2 metres above ground level (PCD, 1995; PCD, 2004; PCD, 2007; PCD, 2009; PCD, 2010a).

A diagram of monitoring station and data transmission system is shown in Figure 2.2. In general, the monitoring network in Thailand consists of the air quality monitoring stations located across Thailand and the monitoring stations comprises automatic air quality monitoring analysers/instruments. For each remote monitoring station, these analysers are connected to a data logger that records the hourly average PM data, which is then transferred by modem to the central computer station (at PCD) through the communication system. At the PCD, the monitoring data is processed, validated and reported to public. The PCD has developed a reporting and warning system with up-to-date information for national air quality in order to communicate information to Thai people and all relevant organizations to protect public health through the Air4Thai.pcd.go.th website and Air4Thai application (PCD, 2019)

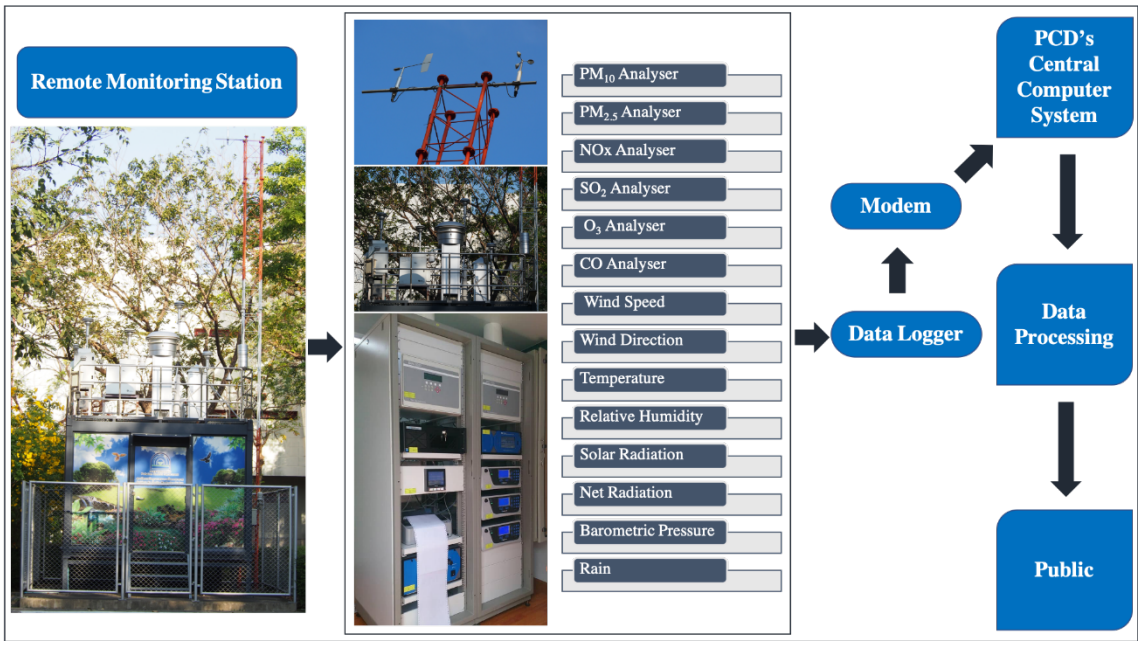
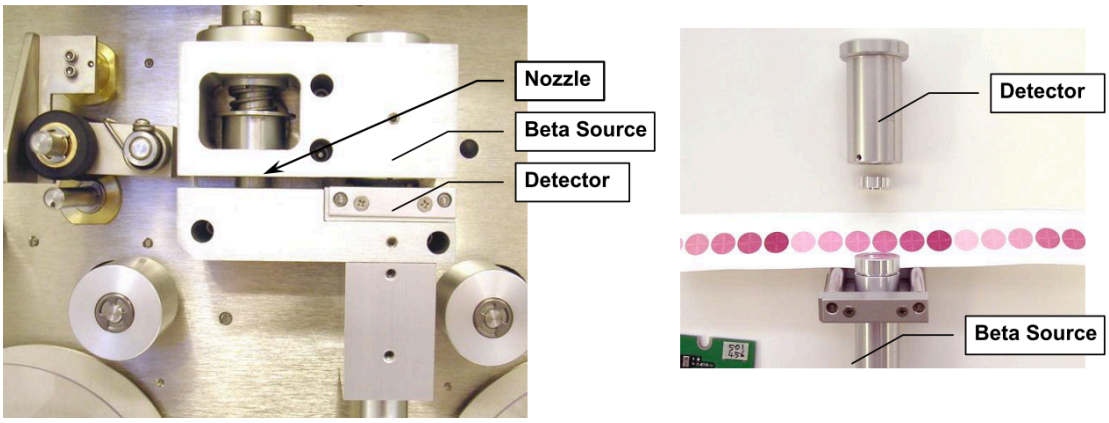



**Figure 2.2:** Diagram of ambient air quality monitoring station and data transmission system

## 2.1.1.3. $PM_{10}$ Monitoring

The measurements from each of the monitoring sites that were used in this thesis were the measurements of $PM_{10}$ made at each site between 2011 and 2015. Measurement of $PM_{10}$ is carried out using the principle of beta ray attenuation mass monitor automatically to measure and record ambient particulate mass concentration levels in mg $m^{-3}$ or µg $m^{-3}$ with a constant source of beta rays 14C (carbon 14) element as shown in Figure 2.3 (Met One Instruments, Inc., 2018; PCD, 2004) Details of $PM_{10}$ measurement and analyser are shown in Table 2.3.




Source: Met One Instruments, Inc. (2018)

**Figure 2.3:** Beta detector, beta source and filter tape use in the instrument (Model BAM 1020)

**Table 2.3:** Summarising of $PM_{10}$ measurement (Model BAM 1020)

| Parameter | Specification |
|---|---|
| **Measurement Principle** | PM concentration by Beta Attenuation |
| **Standard Range** | 0 - 1.000 mg $m^{-3}$ (0 - 1000 µg $m^{-3}$) |
| **Optional Ranges** | 0 - 0.100, 0.200, 0.250, 0.500, 2.000, 5.000, 10.000 mg $m^{-3}$ |
| **Accuracy** | Exceeds US-EPA Class III $PM_{2.5}$ FEM standards for additive and multiplicative |
| **Lower Detection Limit: (2σ) (1 hour)** | < 4.8 µg $m^{-3}$ (< 4.0 µg $m^{-3}$ typical) (8-minute count time) |
| **Lower Detection Limit: (2σ) (24 hour)** | < 1.0 µg $m^{-3}$ |
| **Resolution** | ±1 µg $m^{-3}$ |
| **Precision** | ± 2 µg $m^{-3}$ |
| **Measurement Cycle Time:** | 1 hour |
| **Span Check:** | Nominally 800 µg $cm^{-2}$ |
| **Beta Source:** | C-14 (carbon-14), 60 µCi ±15 µCi (< 2.22 X 106 Beq), Half-Life 5730 years |
| **Flow Rate:** | 16.70 liters/minute |

Source: Met One Instruments, Inc. (2018)

The measurement and timing cycle of the $PM_{10}$ instrument is configured to operate on 1 hour per cycles as a US-EPA designed equivalent method for $PM_{10}$ and the concentration is always an hourly average. The count time for $PM_{10}$ measurement on the instrument is generally set to 4 minutes. At the beginning and the end of each hour of measurement use an 8-minute beta measurement, with a 42-minute air sample period in between, for a total of 58 minutes. The other 2 minutes of the hour are used for tape and nozzle movements during the cycle (Met One Instruments, Inc., 2018). The summarise of the timing cycle is shown in Table 2.4.

**Table 2.4:** Timing of a measurement cycle information taken from Met One Instruments (Model BAM 1020)

| Minute | Activity |
|---|---|
| 00 | The instrument advances the filter tape forward one "window" to the next fresh, unused spot on the tape. This takes a few seconds. The new spot is positioned between the beta source and the detector, and the equipment begins counting beta particles through this clean spot for exactly eight minutes. (I0) |
| ~ 08 | The instrument stops counting beta particles through the clean spot (I0), and moves the tape exactly four windows forward, positioning that same spot directly under the nozzle. This takes a few seconds. The instrument then lowers the nozzle onto the filter tape and turns the vacuum pump on, pulling particulate-laden air through the filter tape on which I0 was just measured, for 42 minutes at 16.70 liters per minute. |
| ~ 50 | The instrument turns the vacuum pump off, raises the nozzle, and moves the filter tape backwards exactly four windows. This takes a few seconds, and puts the spot that was just loaded with particulate back between the beta source and the detector. The instrument begins counting beta particles through the now dirty spot of tape for exactly eight minutes (I3). |
| ~ 58 | The instrument stops counting beta particles through the dirty spot (I3). The instrument uses the I0 and I3 counts to calculate the mass of the deposited particulate on the spot, and uses the total volume of air sampled to calculate the concentration of the particulate in milligrams or micrograms per cubic meter of air. The instrument then sits idle until the top of the next hour. |
| 60 | The beginning of the next hour. The instrument records the just calculated concentration value to memory and sets the analog output voltage to represent the previous hour's concentration. The instrument advances a new fresh spot of tape to the beta measurement area and the measurement cycle starts again. |

Source: Met One Instruments, Inc. (2018)

During the measurement, automatic span checks will perform. 'The cycle while the vacuum pump is on and pulling air through the filter tape as described above the instrument performs a span check. The user may set up the instrument to perform the span check hourly, once per day, or not at all. The instrument also performs a stability test as shown in Table 2.5.

**Table 2.5:** Automatic span checks during the cycle of measurement information taken from Met One Instruments (Model BAM 1020)

| Minute | Activity |
|---|---|
| 08 | The instrument has just finished moving the clean spot to the nozzle and turned the pump on. There is another clean spot of filter tape upstream four windows, between the beta source and the detector. This same spot will stay there for the entire time the pump is on. The instrument begins counting the beta particles through this spot for exactly eight minutes. The measured value is recorded as $I_1$. |
| 16 | The instrument stops counting beta particles and extends the reference membrane between the beta source and the detector, directly above the spot of filter tape that was just measured. The reference membrane is an extremely thin film of clear Mylar held in a metal tongue. The membrane is of known mass density (mg/cm$^2$). The instrument starts counting beta particles for eight minutes again, this time through the membrane and the filter tape spot at the same time. This value is recorded as $I_2$. |
| 24 | The instrument stops counting beta particles through the membrane withdraws the membrane assembly, and calculates the mass density of the membrane. |
| 42 | (Eight minutes before the pump stops) The instrument counts the beta particles through the same spot again (without the membrane) for another eight minutes. This value is recorded as $I_1^1$. |

Source: Met One Instruments, Inc. (2018)

A regular maintenance for the $PM_{10}$ instrument is necessary and carried out by PCD technicians. Monthly, the maintenance completed includes 1) nozzle and vane cleaning, especially, the sample nozzle system needs periodic inspection in order to prevent flow leaks, 2) cleaning $PM_{10}$ inlet particle trap. Every two months, the filter tape rolls are replaced. Quarterly maintenance includes a complete flow system calibration and disassemble and clean $PM_{10}$ inlet. Six monthly maintenance includes testing filter RH, filter temperature sensors, and smart heater function. Twelve months includes cleaning internal debris filter, removing and checking membrane span foil, beta detector count rate and dark count test, cleaning vertical inlet tube, replacing lithium battery if necessary. Finally, every two years maintenance such as rebuilding vacuum pump, replacing nozzle O-ring and pump tubing are undertaken, if necessary (Met One Instruments, Inc., 2018).

Moreover, at the stations at least every 15 days, the air flow rate for $PM_{10}/PM_{2.5}$ is checked and calibrated the accuracy of the mass flow at least every 15 days (PCD, 2004; PCD, 2010a). As shown in Table 2.3, the lower limit of detection of the instrument for an 8-minute count cycle is < 4.8 μg $m^{-3}$ for a 1-hour measurement cycle. At the sites where hourly $PM_{10}$ data was analysed between 2011 and 2015 (Presented in Chapters 3 and 4), there were a small number of hours during which hourly $PM_{10}$ concentrations were below this limit of detection. Across all sites, on averages, only 2.1% of hours were below the limit of detection (see Appendix, Table S2) for a breakdown for each site). During hours when hourly $PM_{10}$ was measured as below the limit of detection, the Pollution Control Department record the $PM_{10}$ concentration value that is measured by the instrument over the one hour cycle. However, the data is also flagged as being below the limit of detection. In this analysis, the measured hourly $PM_{10}$ concentration values during hours when $PM_{10}$ concentrations were below the limit of detection were used, alongside hourly $PM_{10}$ concentrations above the limit of detection. While the measurements below the limit of detection have greater uncertainty, they were retained in this study to avoid the introduction of systematic bias when calculating the annual average concentration and chemical climatology statistics described in Section 2.1.1 (e.g. as compared to other methods of dealing with detection limits (such as replacing with the limit of detection, or half the limit of detection, or removing entirely).

Table 2.3 also lists the precision of the instrument as being ±2 μg $m^{-3}$. The random uncertainty in the measured hourly $PM_{10}$ concentration is associated with 1) the physical nature of the process leading to the emission of beta particles from the decay of 14C, 2) the filter area position during the measurement need to fix in the same position, 3) controlling of the flow rate and, 4) the relative error due to the uncertainly in the absorption cross section (a variation as a function of the chemical composition) (Met One Instruments, Inc., 2018).

#### 2.1.1.4 PM Measurement Data Analysis

In line with the research aims of this thesis, the hourly $PM_{10}$ measurement data described above were analysed to provide information to assess i) spatial variation in the magnitude of annual average PM across Thailand, ii) how variation in hourly PM concentrations (e.g. contribution from high, moderate and low hourly PM concentrations, and hourly PM concentrations occurring in different times of the year and day) contribute to annual PM concentrations and iii) to link this to the contribution of specific drivers of variation in PM concentrations, such as the contribution of different emission source sectors, and the contribution from local vs long-range transport.

To do this required a framework for the statistical analysis of the hourly $PM_{10}$ data, that could be consistently applied across all monitoring sites. A framework, the 'chemical climatology' framework, for the analysis of atmospheric composition data, in relation to specific impacts of atmospheric composition, has been developed and applied to air pollutant measurements in the UK (Malley et al., 2016), and was applied for the first time in this thesis to a national air pollution monitoring network in a south east Asian country.

To link specific impacts of atmospheric composition to the conditions producing them using measurement data, a 'chemical climatology' framework has been developed, that has been applied to quantify the 'impact', 'state' and 'drivers' of the chemical climate specific to a particular impact, e.g. the long-term human health impact of PM (Malley, Braban and Heal, 2014). The definition of three elements are (1) 'Impact' is an identified effect or metric of atmospheric composition, to determine the contributing sources and processes. (2) 'State' is the description of the 'what', 'when' and 'where' of atmospheric composition producing the identified impact including consideration of atmospheric constituents and their temporal and spatial variations relevant to the impact (metric). (3) 'Drivers' are the sources and influences on the atmospheric composition that determine the state, and hence the impact (metric) (Malley, Braban and Heal, 2014). The recent study in U.K. applied the chemical climatology framework to quantify the contributions to long-term health-relevant PM (i.e. annual average $PM_{10}$ and $PM_{2.5}$ concentrations) from different months, chemical constituents and air mass pathways using data from the two UK European Monitoring and Evaluation Programme (EMEP) 'supersites' (Malley et al., 2016). This analysis of the conditions producing annual average PM at these sites showed that frequent, moderate hourly $PM_{10}$ and $PM_{2.5}$ concentrations determined the magnitude of annual average $PM_{10}$

and $PM_{2.5}$ to a greater extent than the relatively infrequent high, episodic $PM_{10}$ and $PM_{2.5}$ concentrations. These moderate $PM_{10}$ and $PM_{2.5}$ concentrations were derived across the range of chemical data captures, seasons and air-mass pathways, in contrast to the highest PM concentrations which tended to associate with specific conditions. For example, the largest contribution to moderate $PM_{10}$ and $PM_{2.5}$ concentrations were accumulated during the arrival of trajectories over marine, UK, and continental Europe areas.

An aim of this study is to apply the 'chemical climatology' framework that has previously only been applied in the UK (Malley et al., 2016; Malley, Braban, and Heal, 2014) to demonstrate the additional information gained from Thailand monitoring network data when a consistent set of statistics are calculated across a set of monitoring sites. The goal in calculating these statistics is to quantify the impact, state, and drivers producing annual average $PM_{10}$ concentrations and to evaluate the influence of long-range transport at different locations across Thailand to understand how conditions associated with timing (both diurnal and seasonal) and spatial trajectory (in relation to neighbouring countries) (Punsompong and Chantara, 2018; Phayungwiwatthanakoon, 2013; Kim Oahn and Leelasakultum, 2011; Niemi *et al.*, 2009) of pollution contribute to health relevant PM concentrations in Thailand, and to understand how these conditions are changing and how they are likely to change in the future see for example Malley et al. (2016).

The overall process for deriving the 'chemical climatology' statistics from the raw hourly $PM_{10}$ data are shown in Figure 2.4 below, and described in more detail in the following sub-sections.

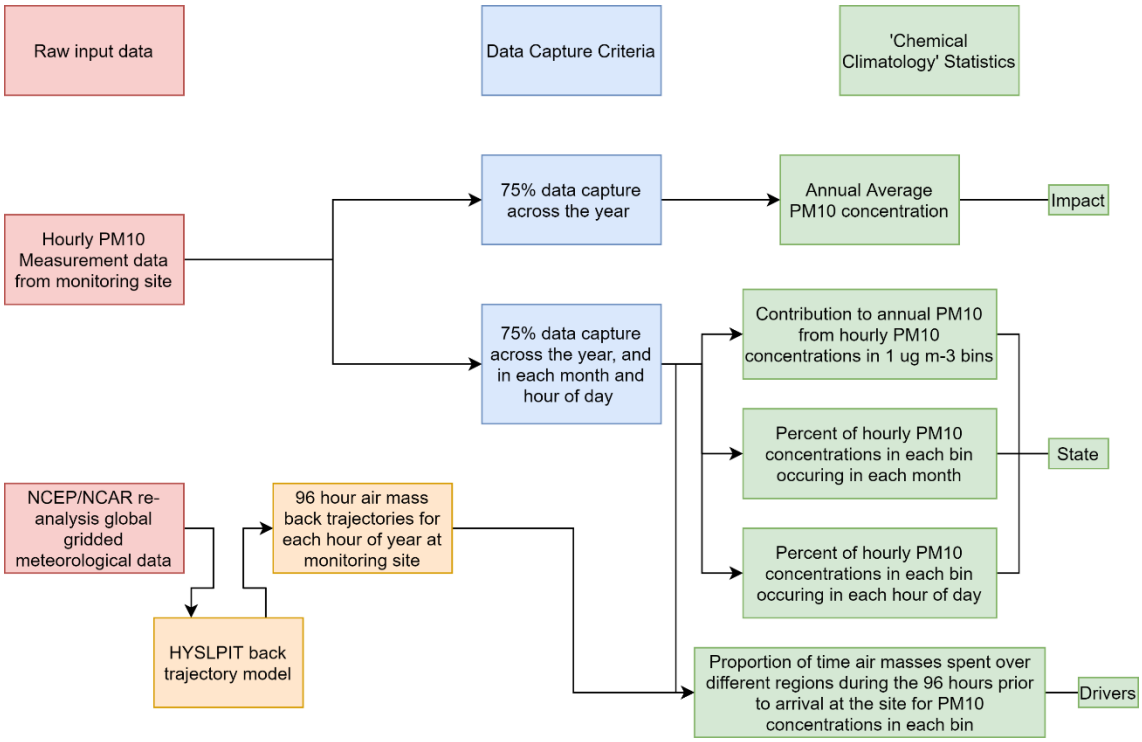



**Figure 2.4:** Flowchart showing how raw hourly $PM_{10}$ timeseries for one year is used to derive set of chemical climatology statistics to characterise impact, state and drivers of annual average $PM_{10}$ at a monitoring site in Thailand.

# 1) PM measurements data

Hourly measurements of total $PM_{10}$ between 2011 and 2015 from the 64 automatic ambient air quality monitoring stations of the Thailand Pollution Control Department (PCD) in 29 provinces across Thailand were used in this analysis. These data were obtained from the PCD (PCD, 2015), and encompassed all continuous hourly $PM_{10}$ measurements made in Thailand between 2011 and 2015. The location of these sites where hourly $PM_{10}$ data were used is shown in Figure 2.5, and the number of sites in different regions in Table 2.6. For the purposes of this analyses, this study grouped the monitoring sites into the following classifications based on the region where the site was located in (e.g. central, Northern, Northeastern, Eastern and Southern Thailand) and its PCD site classification (i.e. whether it was classified as a general or roadside site).

The definition of a ‘general’ site, as specified by the PCD is a measurement site in a residential area and located more than 50 meters from the main road, and ‘roadside’ sites

are sites located in roadside areas, within 10 meters from the main road. In 2015, there were 48 general sites and 5 roadside sites measuring $PM_{10}$, and 10 general sites and 1 roadside site measuring $PM_{2.5}$ across Thailand. Hence, there were substantially fewer monitoring sites measuring $PM_{2.5}$, and only one roadside site for the whole of Thailand (located in Bangkok). The number of sites monitoring $PM_{10}$ and/or $PM_{2.5}$ across Thailand has increased substantially since monitoring began in 1983. From the beginning in 1983 the first air quality monitoring system had only 8 stations located in Bangkok (not on-line system), in 1996 monitoring network (on-line and real-time continuous system) had 38 sites (11 sites in Bangkok and 27 sites in other provinces) then increased to 59 sites in 2010 (17 sites in Bangkok and 42 sites in other provinces) and increased up to 64 stations in 2015 (17 sites in Bangkok and 47 sites in other provinces).

The data from 2011-2015 was chosen to characterise $PM_{10}$ variation for the most recent period for which data was available from across the monitoring network. A time period of 5 years was chosen to allow interannual variability during this period to be assessed. The first step in analysing the data from each monitoring site was to calculate the overall data capture (the percentage of hours in a given time period with a valid hourly $PM_{10}$ concentration measurement). The data capture was calculated across all hours in the year ($DC_{aa}$, Equation 1), as well as for individual months ($DC_{month}$, Equation 2) and hours of the day ($DC_{hourx}$, Equation 3). The data capture during these time periods for each of the sites included in the analysis is shown in Appendix, Tables S3 and S4.

$$DC_{aa} = \frac{\text{Number of hours with valid } PM_{10} \text{ measurements}}{\text{Number of hours in the year}} \quad \text{Equation 1}$$

$$DC_{month} = \frac{\text{Number of hours with valid } PM_{10} \text{ measurements in month}}{\text{Number of hours in the month}} \quad \text{Equation 2}$$

$$DC_{hourx} = \frac{\text{Number of hours with valid } PM_{10} \text{ measurements during hour } x}{\frac{\text{Number of hours in year}}{24}} \quad \text{Equation 3}$$

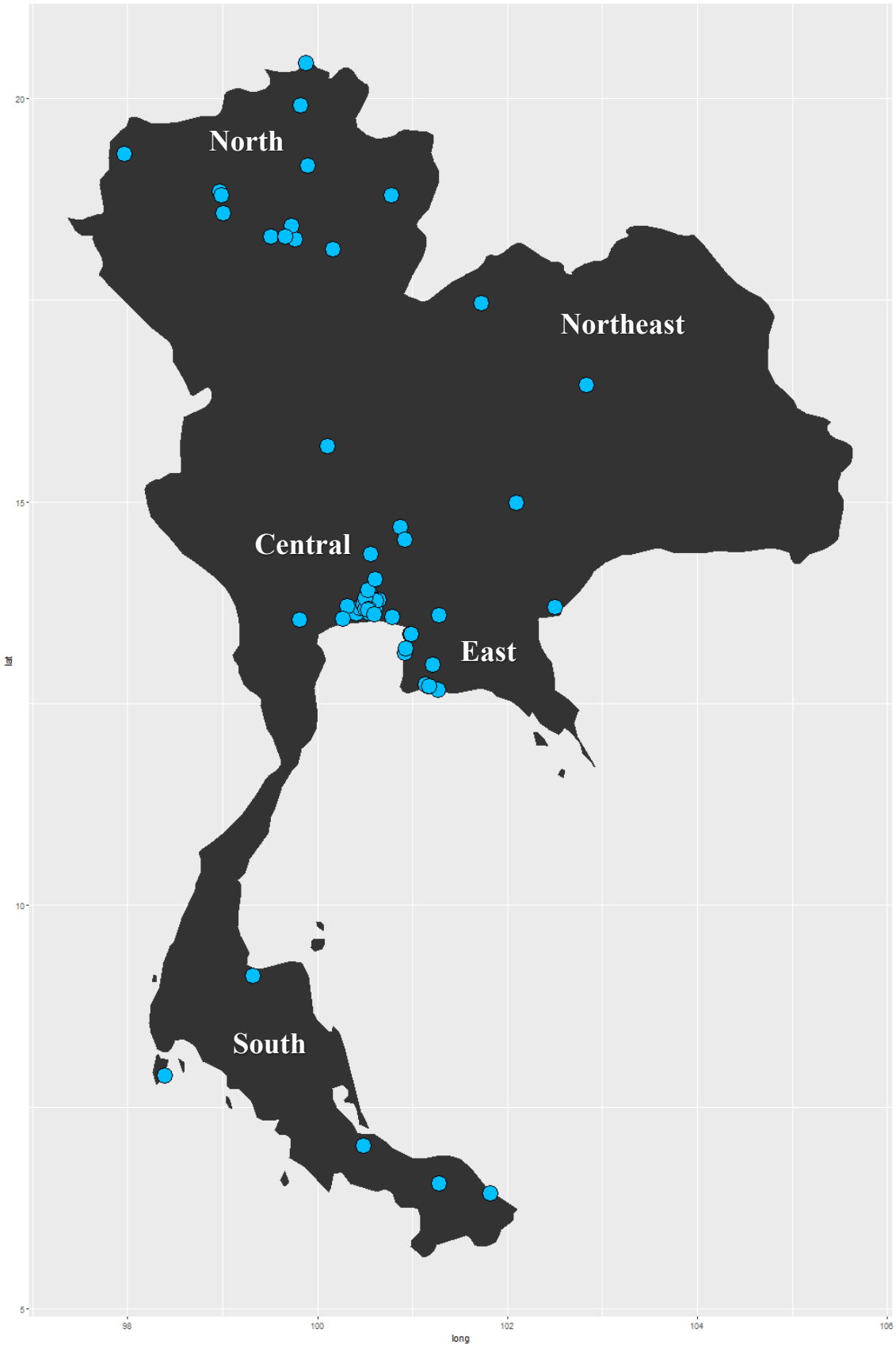



**Figure 2.5:** Map of $PM_{10}$ monitoring site locations in Thailand

**Table 2.6:** Number of automatic ambient air quality monitoring stations in Thailand (PCD, 2015)

| Region | Province | Number of Stations | $PM_{10}$ sites | | $PM_{2.5}$ sites | |
|---|---|---|---|---|---|---|
| | | | General | Roadside | General | Roadside |
| Central Thailand | Bangkok | 17 | 9 | 5 | 2 | 1 |
| | Samut Prakan | 5 | 5 | - | - | - |
| | Pathum Thani | 1 | 1 | - | - | - |
| | Samut Sakhon | 2 | 1 | - | 1 | - |
| | Nonthaburi | 2 | 2 | - | - | - |
| | Phra Nakhon Si Ayutthaya | 1 | 1 | - | - | - |
| | Saraburi | 2 | 1 | - | 1 | - |
| | Ratchaburi | 1 | - | - | 1 | - |
| | **Total** | **31** | **20** | **5** | **5** | **1** |
| Northern Thailand | Chiang Mai | 2 | 1 | - | 1 | - |
| | Chiang Rai | 2 | 2 | - | - | - |
| | Lampang | 4 | 4 | - | - | - |
| | Lamphun | 1 | 1 | - | - | - |
| | Nakhon Sawan | 1 | 1 | - | - | - |
| | Mae Hong Son | 1 | 1 | - | - | - |
| | Nan | 1 | 1 | - | - | - |
| | Phrae | 1 | 1 | - | - | - |
| | Phayao | 1 | 1 | - | - | - |
| | **Total** | **14** | **13** | **-** | **1** | **-** |
| Northeastern Thailand | Khon Kaen | 1 | - | - | 1 | - |
| | Nakhon Ratchasima | 1 | 1 | - | - | - |
| | Loei | 1 | 1 | - | - | - |
| | **Total** | **3** | **2** | **-** | **1** | **-** |
| Eastern Thailand | Rayong | 5 | 4 | - | 1 | - |
| | Chon Buri | 4 | 3 | - | 1 | - |
| | Chachoengsao | 1 | 1 | - | - | - |
| | Sa Kaeo | 1 | 1 | - | - | - |
| | **Total** | **11** | **9** | **-** | **2** | **-** |
| Southern Thailand | Surat Thani | 1 | 1 | - | - | - |
| | Phuket | 1 | 1 | - | - | - |
| | Songkhla | 1 | - | - | 1 | - |
| | Narathiwat | 1 | 1 | - | - | - |
| | Yala | 1 | 1 | - | - | - |
| | **Total** | **5** | **4** | **-** | **1** | **-** |
| **Total** | | **64** | **48** | **5** | **10** | **1** |

## 2) Selection of sites to calculate 'chemical climatology' statistics

This study considered an annual average $PM_{10}$ concentration to be valid if there were at least 75% of hourly observations present during the particular year at the site. However, to perform detailed analysis of the conditions producing annual average $PM_{10}$ concentrations at each site requires not only sufficient observations across the year, but also in each individual month and hour of day. Hence sites were categorised as having sufficient data capture for this further analysis based on three data capture criteria, i.e. above 75% of hourly observations across the year, for each month, and for each hour of the day.

The sites with the most complete $PM_{10}$ data capture were selected to analyse and compare with other sites in each category to assess the consistency of the observations at the most complete site, with others in the same category. The sites which met the data capture criteria described above were grouped into categories based on the region and the location of sites. In Bangkok, the capital city, this study selected both general and roadside sites to analyse data. However, the other regions such as central, Northern, Northeastern, Eastern and Southern Thailand there were only general sites available to analyse. This study first assessed PM concentrations between 2011 and 2015 to understand the most recent PM annual average concentrations, and to account for interannual variability. The annual average between 2011 and 2015 $PM_{10}$ concentration was calculated at all sites that met the annual 75% data capture criteria in at least 3 of the 5 years. The differences between sites in Bangkok (general and roadside site) and across Thailand (general site) were assessed to analyse and compare the conditions producing annual average PM concentrations, including the contribution from different m onths, hours of the day, and during the arrival of air masses that traverse different regions using the air mass back trajectory data for each site.

## 3) Statistical analysis and data analysis

Statistical analysis was focussed on using the combination of measurement data and air mass back trajectories to give insight into how the health-relevant PM metric, i.e. annual mean concentration, was derived. As shown in Figure 2.4 above, and Table 2.7, the statistics calculated in this analysis, grouped into the different components of the 'chemical climatology framework', are consistent with previous applications of this 'chemical climatology' framework to analyse health-relevant $PM_{10}$ and $PM_{2.5}$

concentrations in the UK and this framework showed hourly $PM_{10}$ and $PM_{2.5}$ concentrations determined the magnitude of annual average $PM_{10}$ and $PM_{2.5}$ (Malley et al., 2016). The 'state' of the chemical climate for annual average PM concentrations incorporates the variation in atmospheric composition that produce the annual average PM concentration. In this case the 'state' statistics were derived by first grouping hourly PM concentrations into 1 μg $m^{-3}$ bins. These 1 μg $m^{-3}$ concentration bins group hourly PM concentrations in 1 μg $m^{-3}$ ranges (i.e. hourly concentrations between 0 and 1 μg $m^{-3}$, 1 and 2 μg $m^{-3}$, 99 and 100 μg $m^{-3}$ are grouped into the same bin). Next, for each bin, the percentage contribution of those concentrations to the annual average was calculated, as well as the proportion of concentrations in each 1 μg $m^{-3}$ bin that occurred in each month, and during each hour of the day. 'Drivers' of the chemical climate describe the factors that contribute to the 'state', i.e. the atmospheric composition variation that produces the impact metric. In this case the back trajectory data was used to calculate, for hours during which PM concentrations were assigned to each 1 μg $m^{-3}$ bin, the proportion of time air masses spent over different countries (and the ocean) during the 96 hours prior to arrival at the site.

**Table 2.7:** Chemical climate components, and statistics that will be calculated from monitoring data

| Chemical climate component | Statistic |
|---|---|
| Impact | Annual average $PM_{10}$ (μg $m^{-3}$) |
| State | - Contribution from hourly $PM_{10}$ concentrations assigned to 1 μg $m^{-3}$ bins<br>- Proportion of hours with PM concentrations in 1 μg $m^{-3}$ bins that occur during each month<br>- Proportion of hours with PM concentrations in 1 μg $m^{-3}$ bins that occur during each hour of the day |
| Drivers | Air mass back trajectories<br>- Proportion of time air masses spent over different countries (and the ocean) during the 96 hours prior to arrival at the site for different $PM_{10}$ concentrations |

Finally, a key aspect of this analysis was to identify i) those hourly concentrations that make the largest contribution to annual average, and ii) the conditions producing those concentrations. To make a consistent comparison of concentration ranges between sites, and to account for different hourly PM distributions at different types of sites, this study used percentiles to denote different concentration ranges. These percentile ranges, and their names, are shown in Table 2.8 (very low, low, moderate, high and very high concentrations), and were used for example to assess the percentage contribution of different hourly $PM_{10}$ across the range of hourly concentrations experienced at a site to the annual average concentration.

**Table 2.8:** Percentile groupings and terminology used to explain contribution of different hourly $PM_{10}$ concentrations to annual average values

| PM concentration category at a specific site | Percentiles |
|---|---|
| V**ery low concentrations** | < 5$^{th}$ Percentile |
| L**ow concentrations** | < 25 $^{th}$ Percentile |
| M**oderate concentrations** | 25 $^{th}$ -75 $^{th}$ Percentile |
| H**igh concentrations** | > 75 $^{th}$ Percentile |
| V**ery high concentrations** | > 95 $^{th}$ Percentile |

## 2.1.2 Air Mass Back Trajectories

An air mass back trajectory estimates the path taken by an air mass prior to the arrival of this air mass at a particular location, based on the meteorological conditions during the time that the air mass travels to the site. In this case, the calculation of an air mass back trajectories provided an indication of the path travelled, and regions traversed by an air mass before it arrived at the monitoring sites across Thailand. Air mass back trajectories have been extensively used to analyse air pollution monitoring data, to identify likely source regions during air pollution episodes, as well as characterised those regions most frequently traversed that may make the largest contribution to long-term air pollution concentrations (Fleming et al. 2012). Air mass back trajectories have the advantage of being relatively easy to calculate using meteorological data as input, and identifying the locations that have the largest influence on the air masses arriving at the site. However,

their limitation is that they provide only a linear representation of the path taken by an air mass before it arrives at the site, in contrast to more computationally intensive methods, such as dispersion models that model the broader area which air masses arriving at a site are influenced by (Fleming et al. 2012).

Back trajectories were calculated by running the HYSPLIT model through code written as part of the Openair project (Carslaw and Ropkins, 2012) in the R statistical software (Core Team, 2014). The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2013) requires as input meteorological data, and in this analysis the NCEP/NCAR (Kistler et al., 2001) reanalysis meteorological data was used, and obtained from the National Oceanic and Atmospheric Administration (NOAA), Air Resources Laboratory (http://www.arl.noaa.gov/contact.php). HYSPLIT was run to calculate the latitude, longitude and height of air masses at each hour for four days (i.e. 96 hours) prior to its arrival at the measurement station. These 96-hour back trajectories were calculated for each site for all years with monitoring data available from PCD (http://air4thai.pcd.go.th/webV2/download.php). The selection of 4-day back trajectories, as opposed to longer, or shorter time periods, was a semi-arbitrary choice that reflects the balance between computational efficiency (i.e. the need to calculate back trajectories for 63 sites for 5 years at hourly time steps) and the ability of the back trajectories that are calculated to contrast between the major pathways followed by air masses that are arriving at different monitoring sites in Thailand. 4-day back trajectories have been previously shown to be effective in contrasting between these pathways, both in the UK (Malley, Braban and Heal, 2014). Previous studies in Thailand have estimated back trajectories ranging from 4 to 10 days (Chuang *et al.,* 2016; Kim Oanh and Leelasakultum, 2011; Pongkiatkul and Kim Oanh, 2007), and have shown comparable results in determining the major pathways taken by air masses prior to arrival at a monitoring site.

In this work, the results from the air mass back trajectories were summarised as the percentage of time that air masses spent over different countries and regions (e.g. marine areas) prior to arrival at the monitoring site when a particular hourly $PM_{2.5}$ concentration was measured. This allowed the different pathways taken by air masses to be contrasted between hourly $PM_{10}$ concentrations that were relatively low, and relatively high. We specifically do not interpret the percentage of time spent over different countries as reflecting the percentage contribution of those countries to the measured hourly $PM_{10}$

concentrations, as the back trajectory analysis does not allow for the identification of the geographic location of the emission sources along the back trajectory path taken by air masses. Therefore, in Chapter 3 and 4, the interpretation of the percentage of time spent over different countries by air masses prior to the measurement of different hourly $PM_{10}$ concentrations are used to only contrast between different regions and pathways taken by air masses when different hourly $PM_{10}$ concentrations were measured. When calculating the percent of time spent over different countries/regions for 4-day back trajectories, it was possible to identify differences between different hourly $PM_{10}$ concentrations (see Chapter 3 and 4). However, due to the location of Thailand, when the back trajectory time was increased, e.g. to 10 days, the number of hours back trajectories spent over large areas such as the ocean, or large countries such as China, increased, reducing the proportion of time spent over Thailand, and neighbouring countries. This reduced the amount of useful information gained from the back trajectories, by reducing the contrast in time spent countries relatively close to the monitoring site when using 10 vs 4-day back trajectories.

## 2.2 PM emissions, transport and impact scenario tool use

This study applies a tool called the Long-Range Energy Alternatives Planning-Integrated Benefits Calculator (LEAP-IBC) (Heaps, 2017; Heaps, 2016) at the national scale in Thailand to estimate the contribution of different pollutants from different source sectors to national annual average $PM_{2.5}$ concentrations and to estimate the contribution that emission sources in the country, from the rest of the world and from natural sources make to this metric. The tool then calculates the benefits of emission reductions of pollutants for human health in order to allow policy-makers to estimate the benefits of actions for health and mitigation measures. Therefore, the aims of this study with this tool were 1) to investigate the link between important emission source sectors within and outside Thailand to $PM_{2.5}$ concentration and the potential health impact in Thailand and 2) to develop mitigation scenarios that model the implementation of different mitigation measure to improve air quality in Thailand.

The overall modelling framework is summarised in Figure 2.6. An emission inventory is developed by using the LEAP-IBC tool for all relevant air pollutants ($PM_{2.5}$ and $PM_{2.5}$ precursors) contributing to $PM_{2.5}$ concentrations divided into three parts: 1) in historical years (2010-2017); 2) projection for a baseline scenario from 2018 to 2030; 3) modelling

mitigation measures included in current plans and strategies in Thailand and then modelling additional mitigation measures in key source sectors. The base data is the national energy balance (DEDE, 2010 - 2017), number of vehicles (DLT, 2010 - 2017) and data of livestock, crop production and vegetation fires (FAO, 2018). More detail on the specific data used to apply this framework to Thailand is described in Chapter 5.

The following sections describe the methodology used to estimate emissions for each sector for the historic and baseline scenarios, including the activity data and emission factors used, and the mitigation measures that were modelled, including the assumptions that were used to represent them.

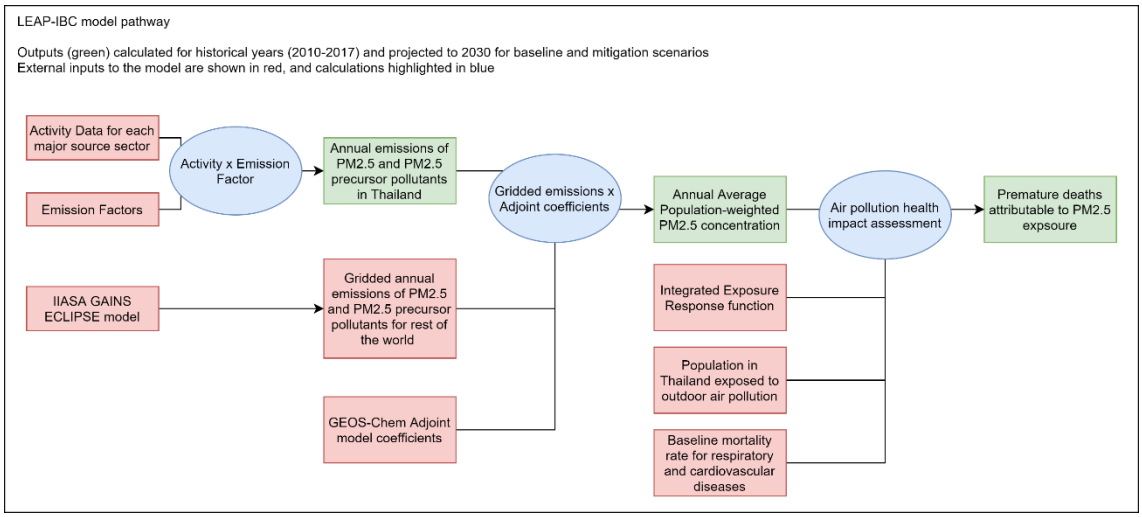



**Figure 2.6:** LEAP-IBC model pathway followed to estimate i) emissions, ii) $PM_{2.5}$ concentrations and iii) $PM_{2.5}$-attributable health impacts for Thailand from 2010 to 2030.

## 2.2.1 Emission calculations

Emissions were calculated for three different broad source sector categories: energy demand (which was subdivided into residential, industry, commercial and public services, agriculture, forestry and fishing, and transportation), energy transformation (electricity generation and oil and gas production, processing and distribution), and non-energy (industrial processes, agriculture and waste) sectors using the LEAP tool. LEAP incorporates an energy planning tool, and therefore the energy demand and energy transformation sectors are linked. The domestic demand for energy from different types of fuels (e.g. electricity, oil products such as gasoline and diesel) determines how much of these fuels are produced to meet this demand by the relevant sectors in energy

transformation (e.g. electricity generation, oil refining), as well as the imports and exports of these fuels. The consumption of fuels under energy demand, and the conversion of fuels from primary feedstock fuels into secondary fuels under energy transformation, all have emissions associated with them. The link between demand and transformation is important in scenario analysis, as it allows the effect of a policy on the whole energy sector to be modelled (e.g. an energy efficiency policy under an energy demand sector may reduce emission directly from that sector, but may also reduce emission associated with the production of that fuel under the transformation sector, if less fuel is required). The non-energy sector emissions were also estimated to provide a complete characterization of emissions from all source sectors, but they are not explicitly linked to the energy sectors as demand and transformation sectors are. Estimation emissions were calculated by multiplying an activity variable for a particular source sector with pollutant specific emission factors. For example, emissions from the residential sector were estimated based on the annual fuel consumption in this sector (the activity variable), taken from official Thai government statistics, multiplied by emission factors expressed as the mass unit of pollutant emitted per unit of energy consumed. In 2010, in the residential sector across Thailand, 68,996 terajoules of liquified petroleum gas (LPG) was consumed. For a particular pollutant, e.g. NOx, an emission factor of 18.7 kilogrammes NOx per terajoule LPG consumed was used, as a default emission factor recommended by the EMEP/EEA (2019) emission inventory guidebook. Multiplying these two values results in an annual emission of NOx from LPG consumption in the Thai residential sector in 2010 of 1,290 tonnes.

The same methods were applied to estimate emissions from all energy and non-energy source sectors, with the only difference being the specific activity variable used to characterise a particular sector, and the specific emission factors associated with that particular activity. The specific activity variables for each source, and the values used in this study are described in Chapter 5. In brief, this study used activity data from Thai official government statistics (DEDE, 2010 - 2017; DLT, 2010 - 2017) on energy consumption and generation, and data from the FAOSTAT database to represent activity in industrial processes, agriculture and vegetation fires (FAO, 2018), and used default emission factors from international organisations (IPCC, 2006; EMEP/EEA,2016; EMEP/EEA, 2013) and from previous studies (Bond et al., 2004; Reddy and Venkataraman, 2002; Andeae and Merlet, 2001; TIFAC, 1991; Tyagi, 1989; Battye et al., 1994). A comprehensive description of the specific data used to estimate emissions from each sector is provided in Chapter 5.

## 2.2.2 Population-weighted Annual Average $PM_{2.5}$ Concentration and health impact assessment modelling

Emissions of $PM_{2.5}$ and $PM_{2.5}$-precursor emissions (black carbon, organic carbon, ammonia, sulphur dioxide and nitrogen oxides) estimated for 2010-2030 using the LEAP tool were then converted into population-weighted annual average $PM_{2.5}$ concentrations across Thailand. The population-weighted annual average $PM_{2.5}$ concentrations was then used to estimate the associated impacts on health (premature mortality) attributable to this level of annual $PM_{2.5}$ exposure. The $PM_{2.5}$ components and $PM_{2.5}$-precursors for which emissions were estimated were chosen because i) they are pollutants for which a robust method of quantifying the sensitivity of changes in their emissions and $PM_{2.5}$ concentrations have been developed using the GEOS-Chem Adjoint model (see below, other pollutants such as VOCs which contribute to secondary organic aerosol formation have not been integrated into the GEOS-Chem Adjoint modelling scheme, and ii) these pollutants make a large contribution to the total mass of PM in the atmosphere, as compared with other pollutants such as heavy metals or persistent organic pollutants which make a minor contribution to the mass of PM (Carnell *et al.*, 2017; Cheewaphongphan *et al.*, 2017; Huang et al., 2014; Putaud *et al.*, 2010; Querol *et al.*, 2009; Hodan and Barnard, 2004; U.S. EPA, 1996).

Emissions for Thailand estimated using the LEAP tool as described above in Section 2.2.1 were combined with gridded emission estimates for all countries outside Thailand from the IIASA GAINS ECLIPSE emission dataset (http://gains.iiasa.ac.at). The ECLIPSE emission dataset contains emission estimates for air pollutants in 0.5 x 0.5 degree grids globally, that are derived from the Greenhouse Gas Air Pollutant Interactions and Synergies model (GAINS) (Amann *et al.*, 2011; Amann *et al.*, 2008). GAINS is an emission inventory and scenario analysis tool that estimates emissions of $PM_{2.5}$ and $PM_{2.5}$ precursor emissions globally from 1990 to 2050 in 5-year timesteps. The methodologies used in the GAINS model to estimate emissions from each source sector are based on international default methods for emission inventory development (IPCC, 2006; EMEP/EEA, 2019), and consistent with those described in Section 2.2.1. The activity variables for each sector in the GAINS model are based on energy consumption and generation data produced by the International Energy Agency (IEA, 2010-2015; https://www.iea.org/data-and-statistics), and agricultural variables provided by Food and

Agriculture Organization (FAO, 2018). The ECLIPSE emission dataset methodology and emission estimates are comprehensively detailed in Stohl et al. (2015).

The national total emissions for Thailand estimated in LEAP were distributed across Thailand based on the spatial distribution of Thai emissions within the ECLIPSE gridded emission dataset, automatically within the LEAP software. The ECLIPSE emission dataset was aggregated from the native 0.5 x 0.5 degree resolution to 2 x 2.5 degree resolution (the resolution of the atmospheric modelling described below). The grids that covered Thailand and that did not cover Thailand were also identified. For those grids covering Thailand, the proportion of emissions assigned to Thailand, and to neighbouring countries, was determined based on the fraction of the population in the grid square living in Thailand vs neighbouring countries (according to the population count in grids at 2.5 arc-minute resolution estimated in the Gridded Population of the World Version 3 dataset). Those ECLIPSE emissions assigned to Thailand were then replaced by the LEAP emissions, with the national total LEAP emissions for each pollutant assigned to the grids covering Thailand based on the fraction of total Thailand ECLIPSE emissions assigned in each grid. This resulted in the ECLIPSE emissions representing emissions in all countries outside Thailand, and the LEAP-derived emissions representing emissions within Thailand. The combination of LEAP-derived emissions for Thailand, gridded across the country, and ECLIPSE gridded emissions for the rest of the world produced a global gridded estimate of emissions for all years between 2010 and 2030 for all scenarios.

These gridded emissions are then combined with the output from the adjoint of the GEOS-Chem global atmospheric chemistry transport model (Bey et al., 2001; Henze et al., 2007). The 'coefficients' produced from the GEOS-Chem Adjoint model quantify the relationship between emissions of a particular pollutant that contribute to $PM_{2.5}$ (BC, OC, other primary PM, $NO_x$, $SO_2$ and $NH_3$) in any location and the change in annual average $PM_{2.5}$ in Thailand. 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 natural (i.e., ocean, volcanic, lightning, soil, biomass burning, biogenic and dust) and anthropogenic (transportation, energy, residential, agricultural, etc.) sources. The model accounts for the transport and hydrophilic aging and removal of primary carbonaceous aerosols (BC and OC) (Park et al., 2003) along with the heterogeneous surface chemistry (Evans et al., 2004), aerosol feedbacks on photolysis rates (Martin et al., 2003), and the partitioning of secondary inorganic aerosols (Park et

al., 2004). The GEOS-Chem Adjoint model calculates the sensitivity of annual average population-weighted $PM_{2.5}$ to an emission change in any 2° × 2.5° grid cells globally (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 annual average $PM_{2.5}$ for each year and emission scenario. Previous applications of GEOS-Chem adjoint coefficients for estimating responses to emissions changes include (Lacey et al., 2017; Lapina et al., 2015; Paulot et al., 2013) (e.g., Henze et al., 2012; Paulot et al., 2013; Lapina et al., 2015; Lacey and Henze 2015; Lacey et al., 2017).

Adjoint coefficients were produced for each pollutant that contributes to population-weighted $PM_{2.5}$ concentration, specifically, 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. Coefficients were not estimated for other pollutants that contribute to $PM_{2.5}$ formation, such as VOCs (forming secondary organic aerosols), heavy metals, polycyclic aromatic hydrocarbons (PAHs), due to the lack of parameterisation of those pollutants within the GEOS-Chem Adjoint model (in the case of VOCs and secondary organic aerosol formation), and due to the small (<1%) contribution that the other pollutants make to the overall $PM_{2.5}$ mass, which is the metric used to quantify the health impacts of $PM_{2.5}$ in this study. The Adjoint coefficients are applied by multiplying, in each grid and for each pollutant, the coefficient by emissions, and summing across all grids to estimate the change in population-weighted annual average $PM_{2.5}$ across Thailand for a particular year for a particular scenario. A limitation of application of the adjoint coefficients is they provide a linear representation of the response of population-weighted annual average $PM_{2.5}$ across Thailand to emissions perturbations, which leads to uncertainty when emission perturbations are large (considered to be approximately >50% for $NO_x$, $SO_2$, and $NH_3$ impacts on $PM_{2.5}$ (Henze et al., 2012; Lee et al., 2015). However, as shown in Chapter 5, the emission changes modelled across Thailand were within this range for all pollutants (Chapter 5).

In 2010, population-weighted $PM_{2.5}$ concentrations across Thailand were set to the value derived from a satellite-based measurement of $PM_{2.5}$ across Thailand, i.e. 28.5 μg $m^{-3}$ (van Donkelaar et al., 2016). The population-weighted $PM_{2.5}$ concentration in 2010 was disaggregated into contributions from emissions of each pollutant from within the country, from outside the country, as well as the contribution from natural background

emissions (mainly sea salt and desert dust). Gridded (2° × 2.5°) $PM_{2.5}$ concentrations in 2010 from natural background emissions were calculated from directly from GEOS-Chem forward model runs, and combined with population count data from the Gridded Population of the World v3 Dataset to determine the natural component of population-weighted $PM_{2.5}$ concentrations across Thailand in 2010. The natural component was assumed to stay constant in future years for all scenarios.

The anthropogenic contribution to population-weighted $PM_{2.5}$ concentrations across Thailand was further disaggregated into contributions from emissions of each primary $PM_{2.5}$ or $PM_{2.5}$ precursor pollutant, and the contribution from Thailand emissions, and from emissions from grid squares outside of Thailand. For each pollutant, for Bangladesh and rest of the world emissions separately, the contribution to population-weighted $PM_{2.5}$ concentrations was calculated by multiplying the adjoint coefficients parameterised for that pollutant by the pollutant emissions in the grids covering Thailand or rest of the world emissions. The sum of these calculations across all grids covering Thailand gave the anthropogenic component of population-weighted $PM_{2.5}$ concentrations across Thailand in 2010, scaled so that the total matched the van donkelaar et al. (2016) population-weighted $PM_{2.5}$ concentration derived from satellite observations.

The impact of scenarios on population-weighted $PM_{2.5}$ concentrations across Thailand in future years were calculated by multiplying the adjoint coefficients for each grid, for each pollutant, by the difference in emissions between 2010 and the future year in a particular scenario. The change in emission in the grids covering the rest of the world, in the baseline scenario, were estimated from the ECLIPSE current legislation scenario (Stohl et al., 2015). The change in emissions in the grid covering Thailand were calculated by subtracting the emissions of each pollutant in the future year from the values in 2010. The sum of the coefficient × change in emission for each pollutant for each grid then provided the estimate of the change in population-weighted $PM_{2.5}$ concentrations in the future year due to changes in emissions of each pollutant for a particular scenario compared to 2010. The uncertainties associated with estimating future population-weighted $PM_{2.5}$ concentrations based on the application of these linearised GEOS-Chem Adjoint coefficients is that non-linear atmospheric chemical processes that result in changes in $PM_{2.5}$ concentrations resulting from future changes in emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors are not taken into account. These uncertainties are largest for secondary inorganic aerosol formation (compared to primary $PM_{2.5}$ emissions), but previous studies

have shown that significant differences to forward model results only occur for emission perturbations above 50% (Henze et al., 2012; Lee et al., 2015).

Health impacts attributable to exposure to $PM_{2.5}$ across Thailand were estimated using standard health impact assessment methods applied by the World Health Organisation and Global Burden of Disease project to estimate the number of premature deaths attributable to $PM_{2.5}$ exposure in Thailand. There are many calculation methods that have been used to quantify the change in premature deaths for a particular level of exposure in excess of a minimum risk exposure level (Burnett et al. 2014; Anenberg *et al.*, 2010). These methods vary in terms of the air pollution exposure metric used (e.g. 24-hour average, annual average), and the concentration-response function used to quantify the increased risk of premature mortality from a particular level of exposure. The change in premature mortality estimated from exposure to $PM_{2.5}$ in Thailand was estimated using the equation below, for consistency with the methodologies used in the most recent global assessments of air pollution impacts on human health by Global Burden of Disease and WHO:

$$\mathbf{\Delta Mort = y_0(RR_{IER} - 1/RR_{IER})Pop.}$$

*Where:* *(Equation 4)*

- $\Delta$Mort is the change in mortality attributable to a change in air pollution concentrations
- $y_0$ is the baseline mortality rate for the particular cause of death associated with air pollution exposure
- Pop. is the population exposed to the population-weighted $PM_{2.5}$ concentrations
- $RR_{IER}$ is Integrated Exposure Response functions that quantify the RR for mortality for $PM_{2.5}$ exposures up to very high levels (10,000 $\mu g\ m^{-3}$)

Equation 4 is based on the equation used to estimate $PM_{2.5}$-attributable mortality in the Global Burden of Disease studies of mortality causes and risks (Cohen et al. 2017). The $PM_{2.5}$ exposure estimate was derived as described above as the population-weighted annual average $PM_{2.5}$ concentration across Thailand. The exposed population and baseline mortality rate for each age group and disease category were obtained from the UN Population Division statistics, and Global Burden of Disease project 2017 (Global Burden of Disease Study 2017-See Appendix, Table S1) and http://ghdx.healthdata.org/gbd-

2017). The Integrated Exposure Response function, described in Burnett et al. (2014) was used to derive the relative risk, the increased risk of premature death for a particular exposure level, for each disease category. The IER functions are derived by integrating the result from epidemiological studies on the effect of exposure to ambient air pollution, household air pollution, second hand smoke and active smoking on premature mortality from ischaemic heart disease, cerebrovascular disease, lung cancer, chronic obstructive pulmonary disease and acute lower respiratory infection (in children, other diseases are adults (>30 years old). This provides a continuous function that quantifies the relative risk of premature deaths from very low concentrations (~5 μg $m^{-3}$) to very high $PM_{2.5}$ concentrations (10,000 μg $m^{-3}$). The IER functions were developed because the majority of epidemiological studies that have been conducted to quantify the associated between ambient air pollution exposure and health effects have been conducted in Europe and North America, where annual $PM_{2.5}$ concentrations are substantially lower than in many parts of the world, including in Thailand (see Chapter 3). Therefore, by integrating available ambient air pollution epidemiological studies with those developed for sources of much higher PM exposure, such as household air pollution and smoking, a function is developed that quantifies the relationship between PM exposure and risk of premature mortality at ambient $PM_{2.5}$ exposures commonly experienced in Asia, Africa and other parts of the world that lack direct epidemiological relationships. Limitations and uncertainties with this approach is that it assumes that populations outside North America and Europe (where studies have been conducted) respond similarly to a given level of $PM_{2.5}$ exposure, which may not be the case due to differences in the underlying health status of the population. It also assumes that the total mass of $PM_{2.5}$ is the most significant indicator of the toxicity of exposure across the sources of $PM_{2.5}$ exposure that are integrated together (i.e. ambient, household and smoking), and that the different composition of $PM_{2.5}$ from these sources does not have an impact. Equation 1 was applied for populations in five year age groups separately, for the five disease categories, and then summed to estimate the total health burden from a particular population-weighted $PM_{2.5}$ concentration resulting from a particular set of emissions for a particular year/scenario.

This methodology was chosen because i) it utilises the annual average $PM_{2.5}$ concentration as the exposure metric, i.e. a metric quantifying long-term exposure to $PM_{2.5}$ which has been shown to capture a greater proportion of the totality of the air pollution health impact than short-term (e.g. daily) average exposure metrics

(REVIHAAP, 2013), ii) it utilises a concentration-response function that characterises the relative risk of air pollution exposures up to the levels of $PM_{2.5}$ concentrations that are experienced in Thailand. Other concentration-response functions derived solely from studies conducted in Europe and North America characterise the relative risk for a small range and lower $PM_{2.5}$ concentrations that are typical in those regions, but which are lower than those experienced in Thailand. In addition, it focusses on quantifying the number of premature deaths attributable to $PM_{2.5}$, which have been shown to contribute the largest fraction of the overall burden of disease (e.g. when quantified as the number of disability adjusted life years (DALYs) compared to non-fatal health outcomes. However, it is noted that exposure to $PM_{2.5}$ has been associated with a range of non-fatal morbidity impacts, including asthma exacerbation, preterm birth, and diabetes, which have not been quantified here.

# Chapter 3: Assessment of the contribution of long-range transport to annual $PM_{10}$ concentrations in Thailand

## 3.1 Introduction

This chapter focuses on the conditions producing annual average $PM_{10}$ concentrations at general air monitoring sites in Northern and Southern Thailand between 2011 and 2015. Sites in Northern and Southern Thailand were assessed together in this chapter because in both regions biomass burning has been shown to produce short-term peaks in PM concentrations (Punsompong and Chantara, 2018; Phayungwiwatthanakoon, 2013; Kim Oahn and Leelasakultum, 2011). However, the contribution of these short-term episodes to the annual average PM concentrations that are relevant for human health impacts from long-term PM exposure has not been investigated.

To understand the conditions producing annual PM concentrations in Northern and Southern Thailand, this chapter applies the 'chemical climatology' framework which has previously been developed and applied at sites in the United Kingdom (Malley *et al.*, 2016; Malley, Braban and Heal, 2014) to assess the contribution of hourly $PM_{10}$ concentrations from short-term biomass burning episodes to the annual average $PM_{10}$ concentrations including the contribution from different months of the year, and hours of the day. A back trajectory analysis is used to evaluate the influence of long-range transport and biomass burning in producing short-term peak $PM_{10}$ episodes across Thailand, by assessing the proportion of time air masses spend over different countries, when different hourly $PM_{10}$ concentrations occur. The aim of this analysis is to assess whether these 'chemical climatology' statistics can increase the information derived from a compliance monitoring network in Thailand and effectively link the magnitude of annual $PM_{10}$ concentrations with the variation in hourly $PM_{10}$ concentrations that produce it.

Recently, the study from Chandra et al. (2017) reported that the major sources of biomass burning emission in the Indo-China Peninsula region (the mainland in Southeast Asia

such as Myanmar, Thailand, Laos, Cambodia, Vietnam and etc.) were burning of agricultural crop residues, forest burning associated with land clearing and deforestation, and domestic burning of biofuels. Another study also showed that the majority sources of air pollutant emissions in the upper northern, lower northern and northeast Thailand were associated with the ambient PM concentration from open biomass burning from crop residue and forest fires which linked to the status of air pollution in Thailand (Phairuang, Hata and Furuuchi, 2017). Boonman, Junpen and Garivait (2014) found that during dry season (December to March) between 2009 and 2011 in Northern Thailand, the critical haze situation was mainly associated with open biomass burning, forest fires and agricultural burning and the most critical burning occurred in 2010. Junpen *et al.* (2018) showed that agricultural burning activities result in the higher level of $PM_{10}$ concentration in Thailand.

In southern Thailand, high short-term peaks in $PM_{10}$ concentrations are mostly associated with regional haze episodes, the timing of these transboundary episodes from biomass burning vary. For example, the PCD reported a haze episode in southern Thailand in 2015 that occurred between June, 1$^{st}$ and October, 30$^{th}$, during which $PM_{10}$ levels at the air quality monitoring stations in this region exceeded the Thai 24 – hour average $PM_{10}$ standard of 120 $\mu g\ m^{-3}$ for 10 days (7% of the monitoring period) (PCD, 2015). This period coincided with forest and agricultural burning in the forests of Sumatra and Borneo islands, Indonesia and elevated air pollution levels were recorded across Southeast Asia in Thailand, Malaysia and Singapore (Field et al., 2016). In 2014, the $PM_{10}$ level did not exceed the standard in Thailand (PCD, 2015), however, in June 2013, the peak period for transboundary haze occurred at this time (Betha, Behera and Balasubramanian, 2014).

The consequences of these high, short-term $PM_{10}$ concentrations associated with the biomass burning periods in northern and southern Thailand for the magnitude of the $PM_{10}$ impact metric that is most associated with human health impacts (i.e. the annual average $PM_{10}$ concentrations) has not been evaluated in previous studies assessing air pollution in northern and southern Thailand. Therefore, this analysis applies a common 'chemical climatology' framework to evaluate the variation in hourly $PM_{10}$ concentrations that determines the magnitude of annual $PM_{10}$ concentrations in each region. This framework is important because it can assess how biomass burning events influence annual average concentrations and how they contribute to long-term PM exposure relevant for human health. The specific focus is on how a standard set of statistics calculated for each

monitoring site can be used to assess the relative contribution of high hourly $PM_{10}$ concentrations that occur during biomass burning periods in northern and southern Thailand to determining the magnitude of annual $PM_{10}$ concentrations, and exceedance of national air quality standards. This study therefore: i) assesses the potential effectiveness of reducing biomass burning PM emissions on achieving national and international air quality targets and guidelines related to annual $PM_{10}$ concentrations; and ii) provides a methodology that could be extended to monitored or modelled PM concentrations in other locations to effectively link the drivers of elevated $PM_{10}$ concentrations during particular periods to regulatory/impact metrics.

## 3.2 Methods

The chemical climatology approach outlined in the main methods chapter (Chapter 2) was applied to the monitoring data at sites in Northern and Southern Thailand to understand the influence of long-range transport in determining annual $PM_{10}$ concentrations in these regions. At each general site for each year, the annual average $PM_{10}$ concentration was calculated from the hourly time series. In addition, the contribution to annual $PM_{10}$ from hourly $PM_{10}$ concentrations divided into 1 $\mu g\ m^{-3}$ bins was calculated, and the proportion of hourly concentrations in each bin occurring in each month of the year and hour of the day were also calculated. Four-day air mass back trajectories arriving at the site at each hour during the year were calculated (See Section 2.1.2 in Chapter 2 for a description of how these back trajectories were calculated), and the country over which the trajectory was located at each hour prior to arrival at the site was determined. Hence, the proportion of time which trajectories spent over Thailand, the ocean and neighbouring countries in the 4 days prior to arrival at the sites for hours with hourly $PM_{10}$ concentrations in each $1\mu g\ m^{-3}$ bin was calculated. Moreover, meteorological conditions, such as wind speed, wind direction and temperature, were analysed with meteorological data to consider how they vary with hourly $PM_{10}$ concentrations (https://www.esrl.noaa.gov/). Those years between 2011 and 2015 were analysed by using these statistics at sites that had sufficient data capture which was more than 75% of the hourly observations across the year, as well as more than 75% of hourly observations in each months of the year, and for each hour of the day (for additional details, see Chapter 2). The screening of data using these criteria yielded 14 sites in Northern Thailand and 3 sites in Southern Thailand that could be used for the analysis.

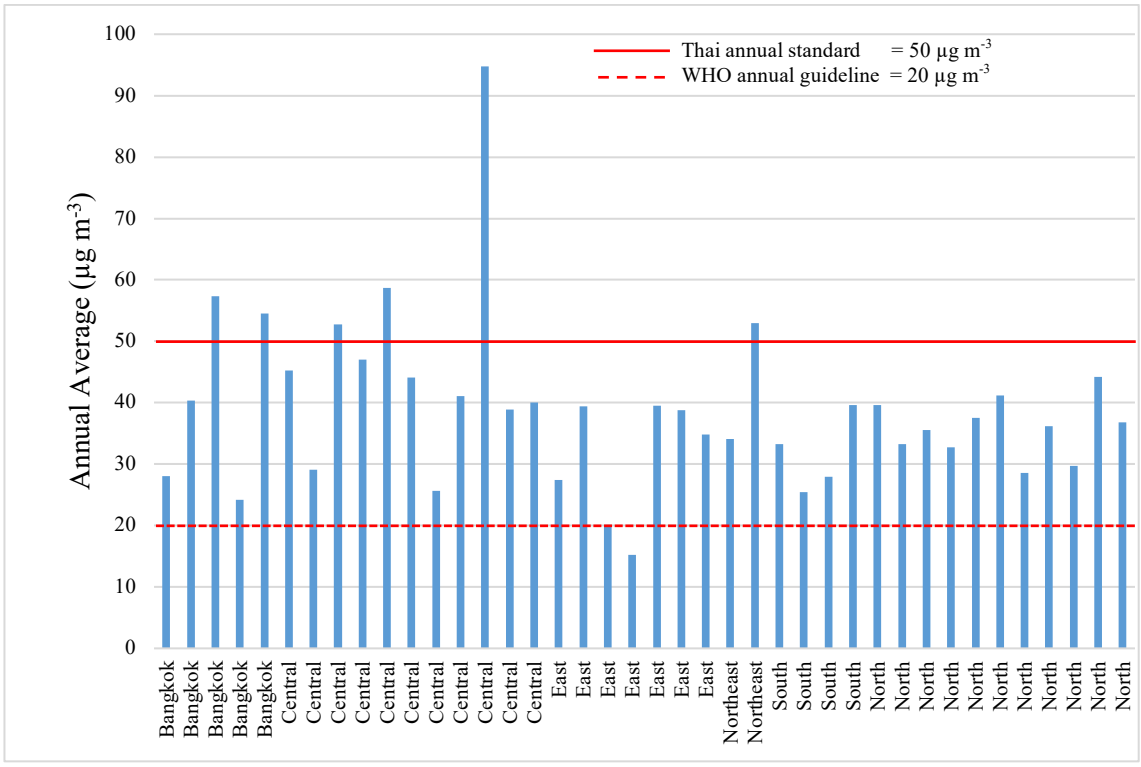
For the $PM_{10}$ measurement results, values are reported to one decimal place due to the uncertainty in the hourly $PM_{10}$ measurement (See section 2.1 for discussion of measurement uncertainty), and to zero decimal place for percentage values.

# 3.3 Results

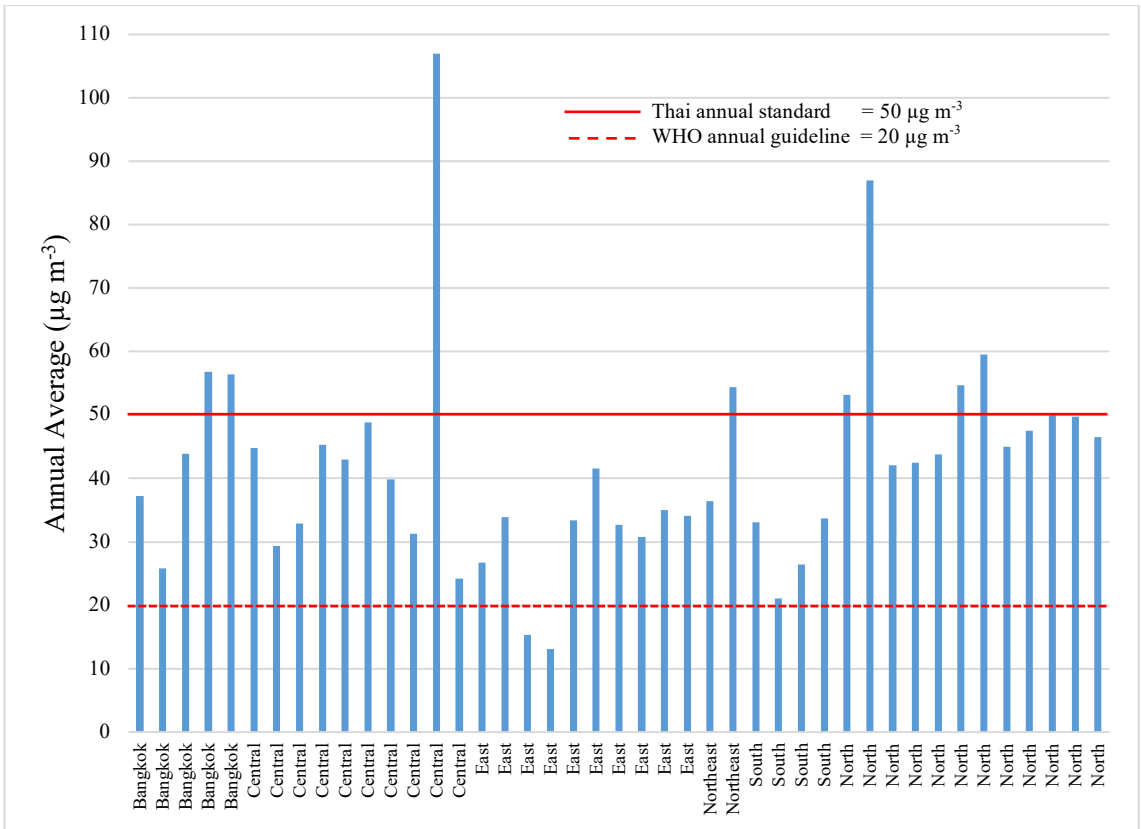
## 3.3.1 Annual average concentrations

Thailand has an annual average standard for $PM_{10}$ of 50 μg $m^{-3}$. Variation of the annual average $PM_{10}$ concentrations for individual years between 2011 and 2015 at these monitoring sites are shown in Figures 3.1 and 3.3. In 2011 (Figures 3.1 (a) and 3.3 (a)), the main difference compared to the 2011-2015 average annual $PM_{10}$ concentrations (Figure 3.2) was that across all sites in Northern Thailand, annual concentrations were much lower than the average. Across all sites in Northern Thailand, annual $PM_{10}$ concentrations were on average 8.6 μg $m^{-3}$ (19%) lower than the 2011-2015 annual $PM_{10}$ concentrations and ranged between 5.3 μg $m^{-3}$ lower and 14.3 μg $m^{-3}$ lower. These reduced annual $PM_{10}$ concentrations were observed at all sites in the Northern Thailand region, from sites in urban centres such as Chiang Mai as well as sites in smaller cities. This meant that in Northern Thailand, the 2011-2015 average annual $PM_{10}$ concentrations exceeded Thailand's annual standard at 4 sites in Northern Thailand, but no sites exceeded the standard in 2011. In contrast, in southern Thailand, the three sites showed a consistent range of annual $PM_{10}$ concentrations between 2011 and 2015, with no exceedances of the $PM_{10}$ standard in any year at these sites.

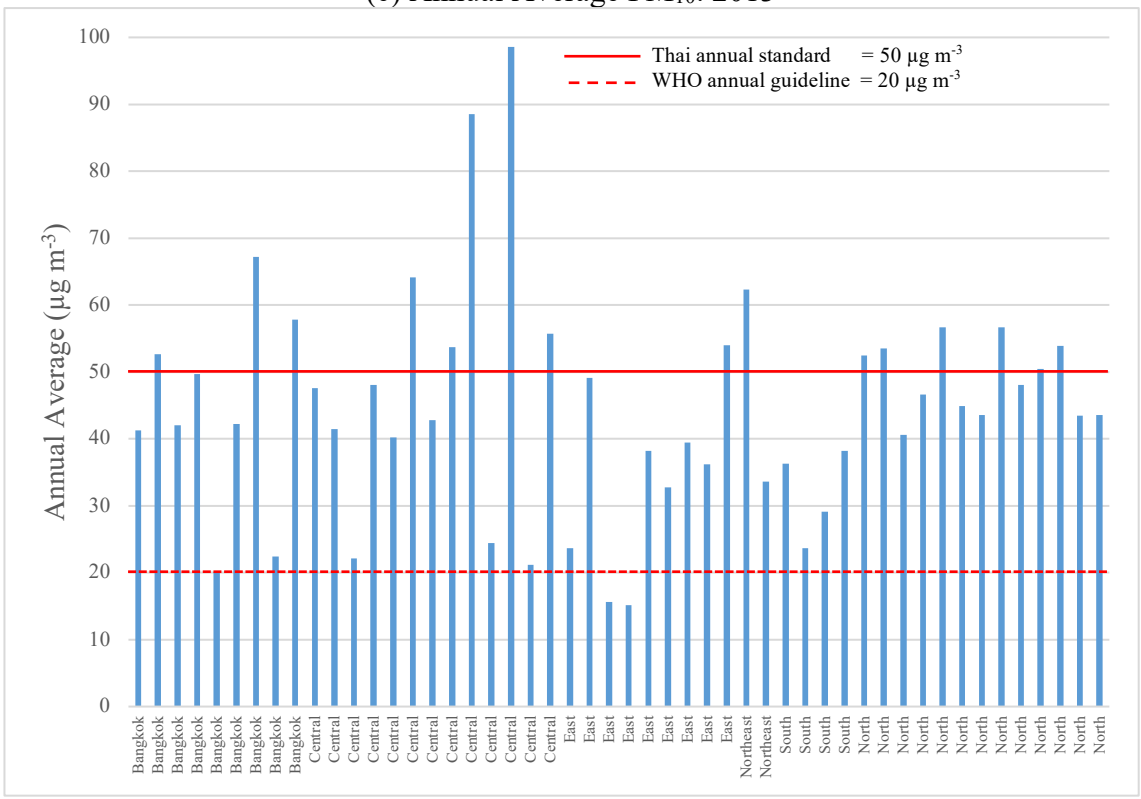
(a) Annual Average $PM_{10}$: 2011



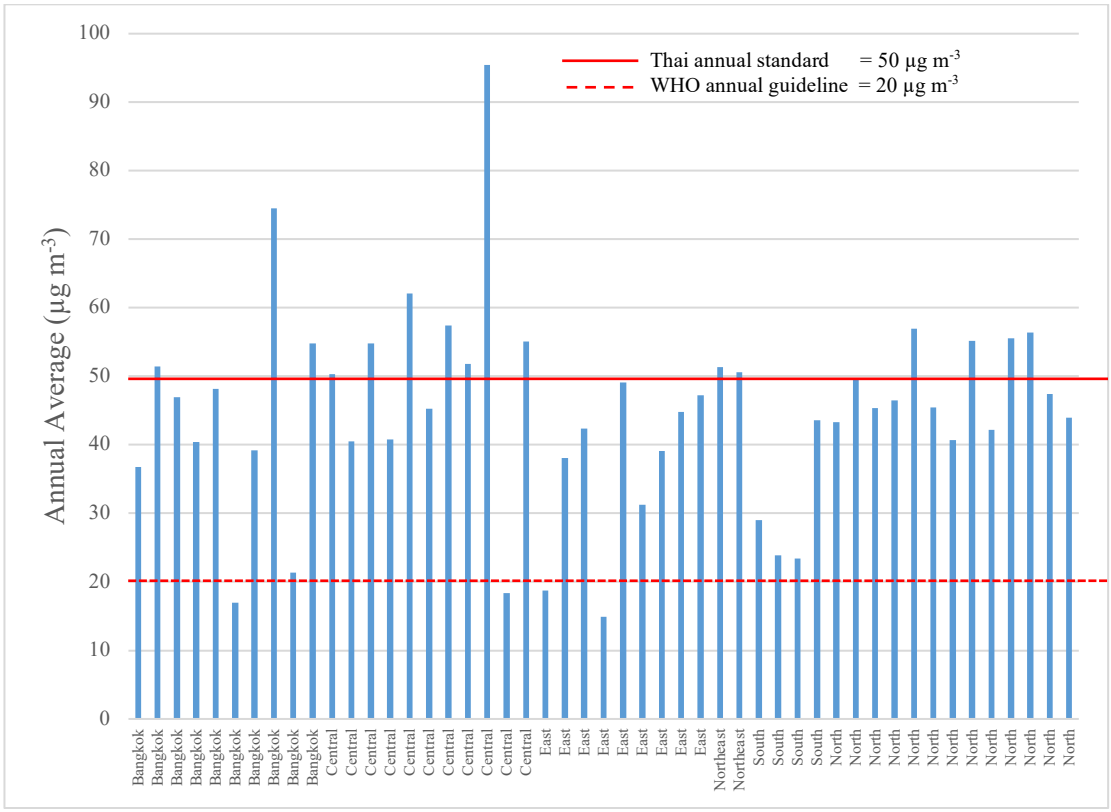

(b) Annual Average $PM_{10}$: 2012



(c) Annual Average $PM_{10}$: 2013




(d) Annual Average $PM_{10}$: 2014



(e) Annual Average $PM_{10}$: 2015

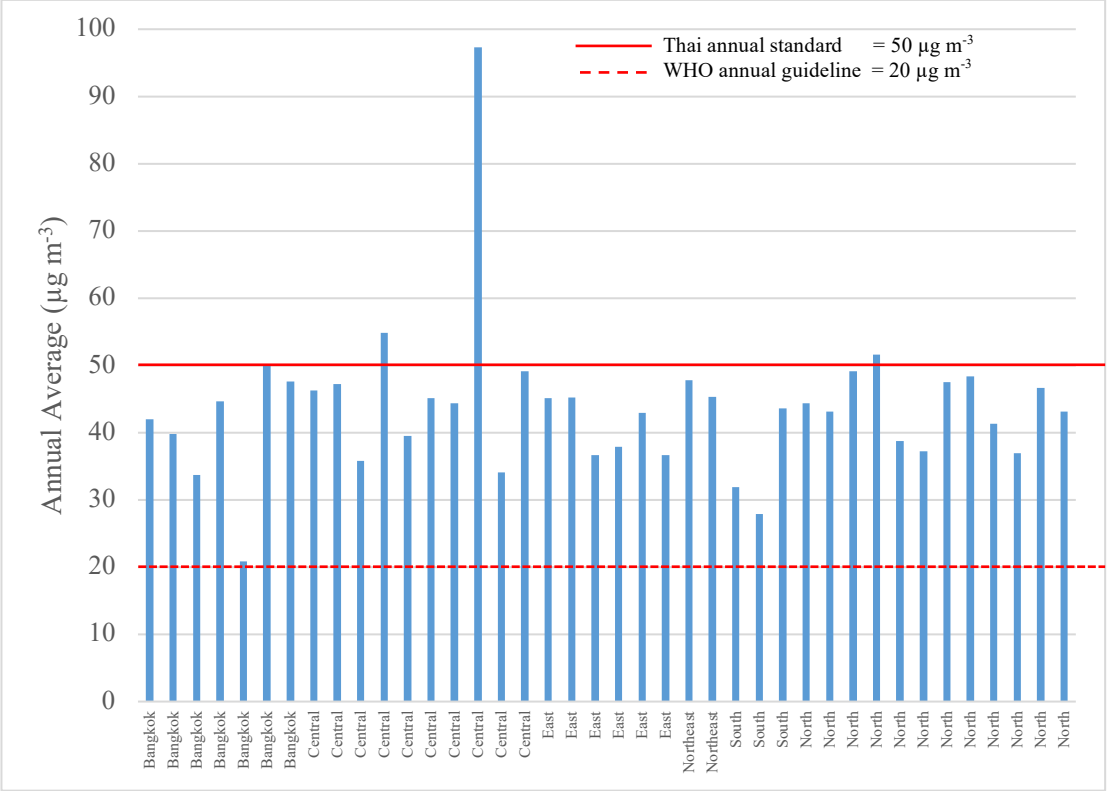



**Figure 3.1:** The annual average $PM_{10}$ concentrations for individual years between 2011 and 2015

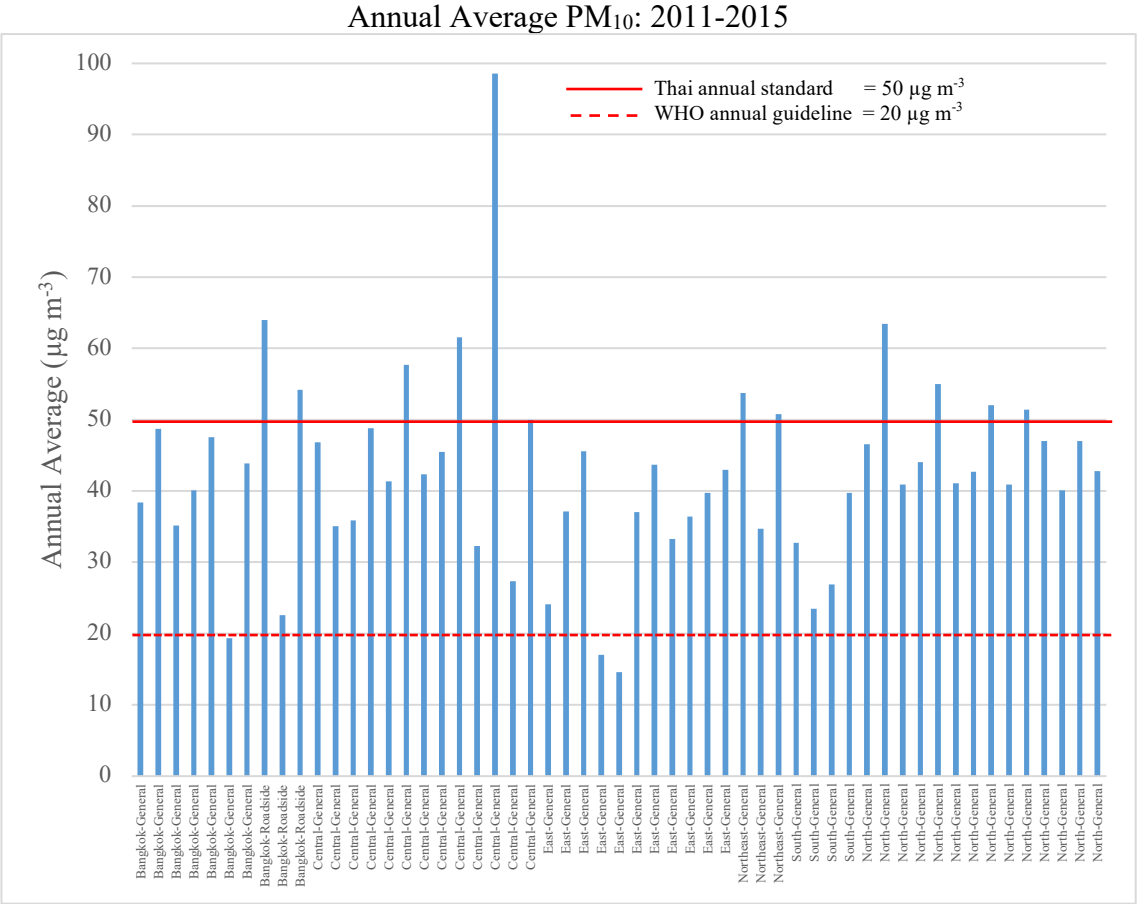
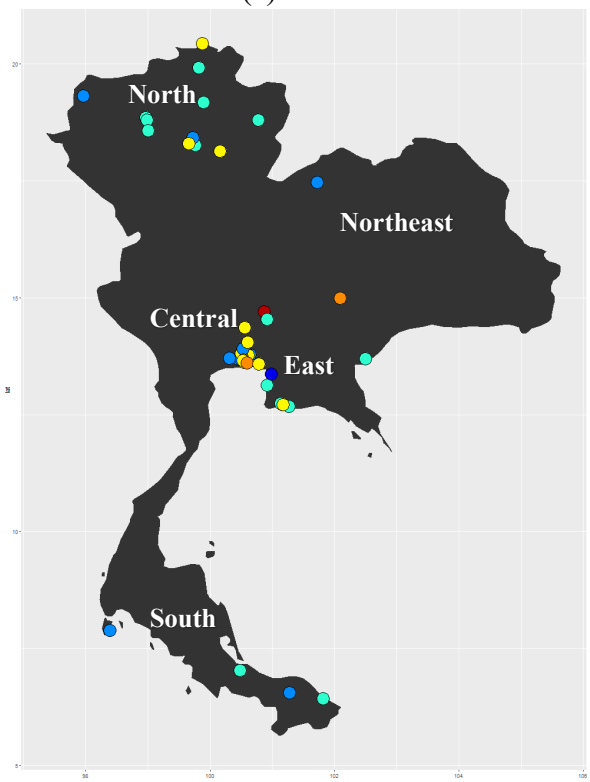
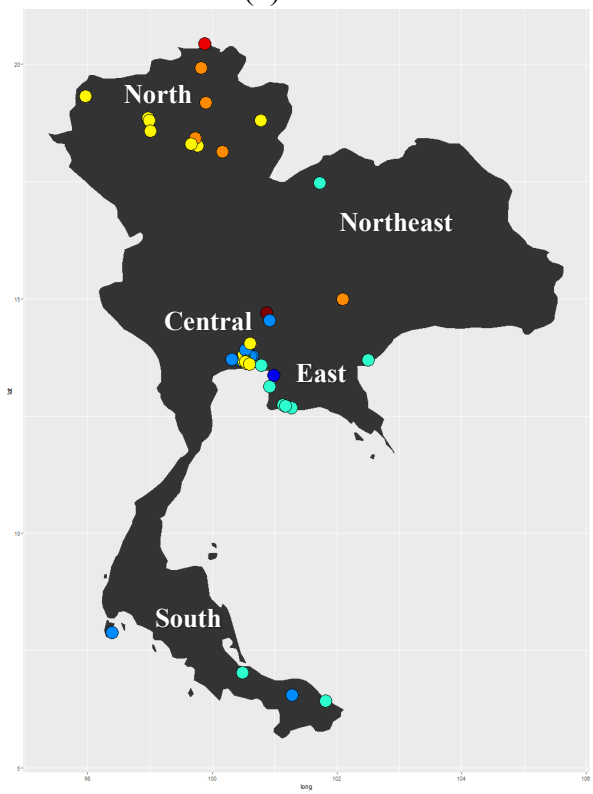



**Figure 3.2:** The comparison of annual average $PM_{10}$ concentrations across Thailand between 2011 and 2015

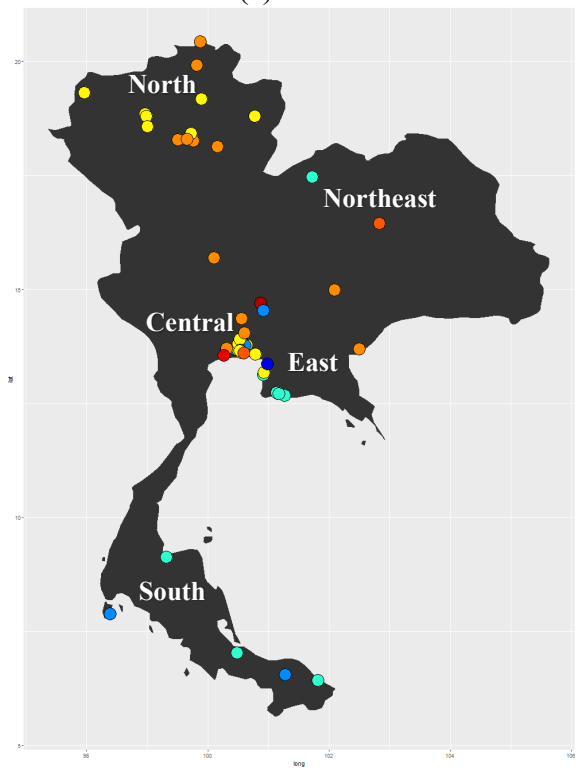
(a) 2011



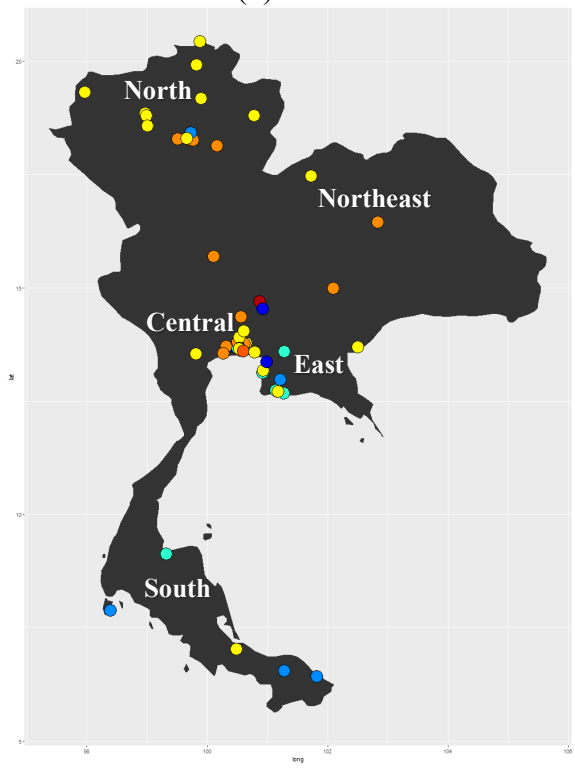

(b) 2012




(c) 2013




(d) 2014



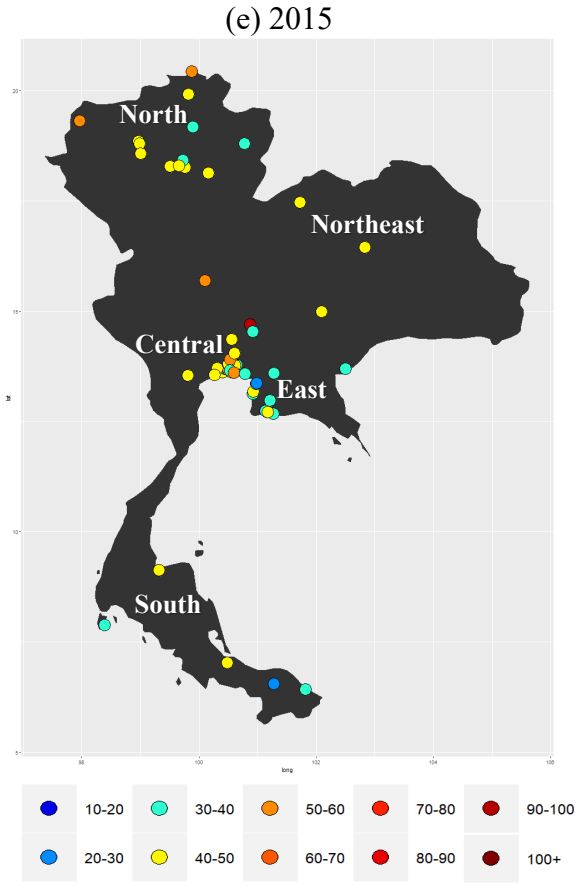



**Figure 3.3:** Maps of study area in Thailand for an individual year between 2011 and 2015 showed annual average $PM_{10}$ concentrations

The 2011-2015 average annual $PM_{10}$ concentration exceeded the Thai National standard at 12 sites across Thailand (Figures 3.2 and 3.4). The annual average was generally higher in central and northern Thailand compared to southern Thailand. For example, in southern Thailand, annual $PM_{10}$ concentrations ranged from 20 – 40 µg $m^{-3}$. In contrast, annual $PM_{10}$ concentrations in northern Thailand were between 30 up to 60 µg $m^{-3}$. In central Thailand and Bangkok, annual $PM_{10}$ concentrations had a much wider range across all sites, from 10 up to 100 µg $m^{-3}$ as shown in Figure 3.1 and Figure 3.2. Across all sites that met data capture criteria, the median annual $PM_{10}$ across Northeast sites (3 sites) was higher than the North (14 sites) and East (8 sites), and sites in South of Thailand (3 sites) had the lowest concentrations (Figure 3.5). In addition, the annual $PM_{10}$ concentrations across central Thailand at roadside sites had a much wider range compared to general sites in the same region (Figure 3.5).

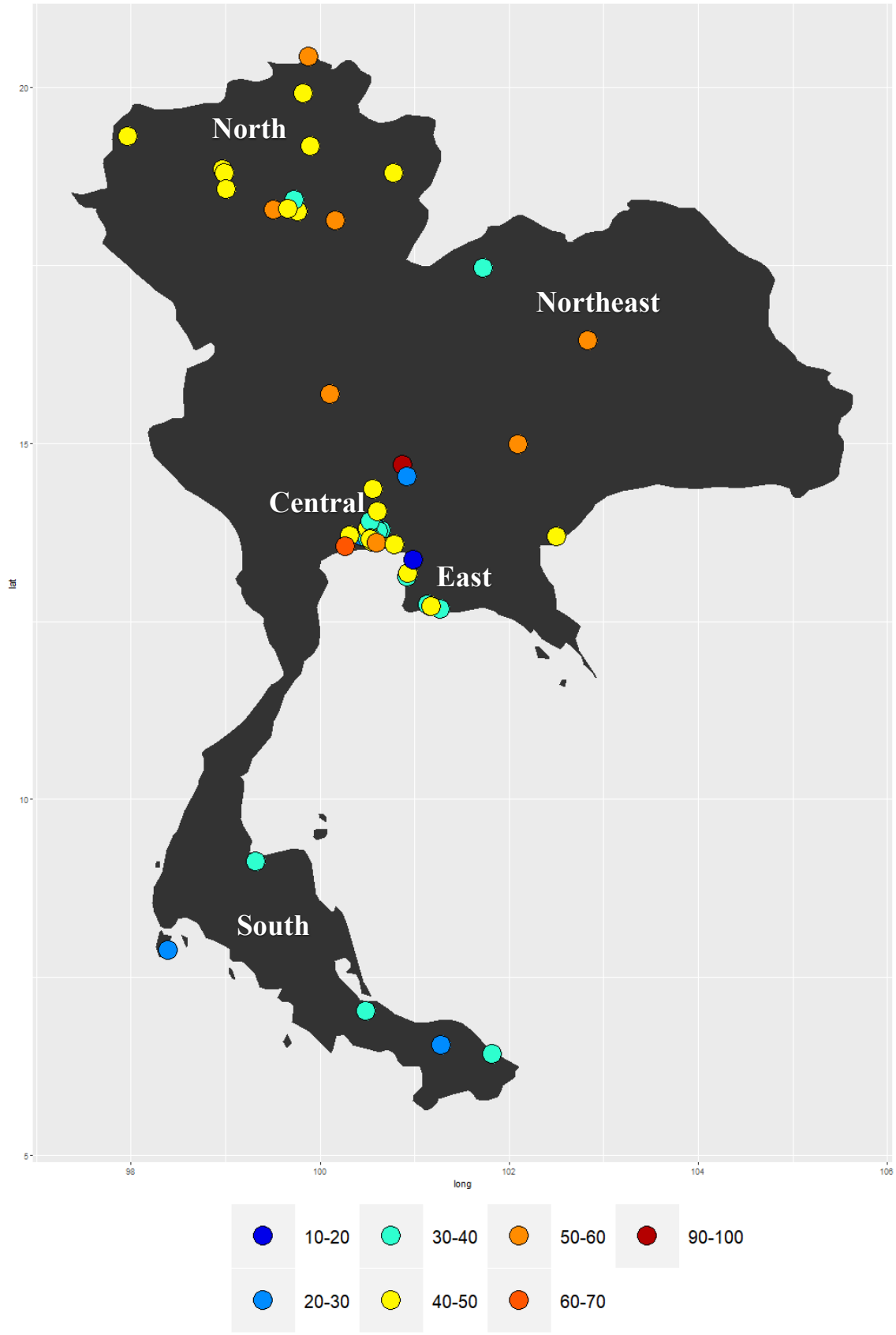



**Figure 3.4:** Map of study area in Thailand between 2011 and 2015 showing the annual average $PM_{10}$ concentrations

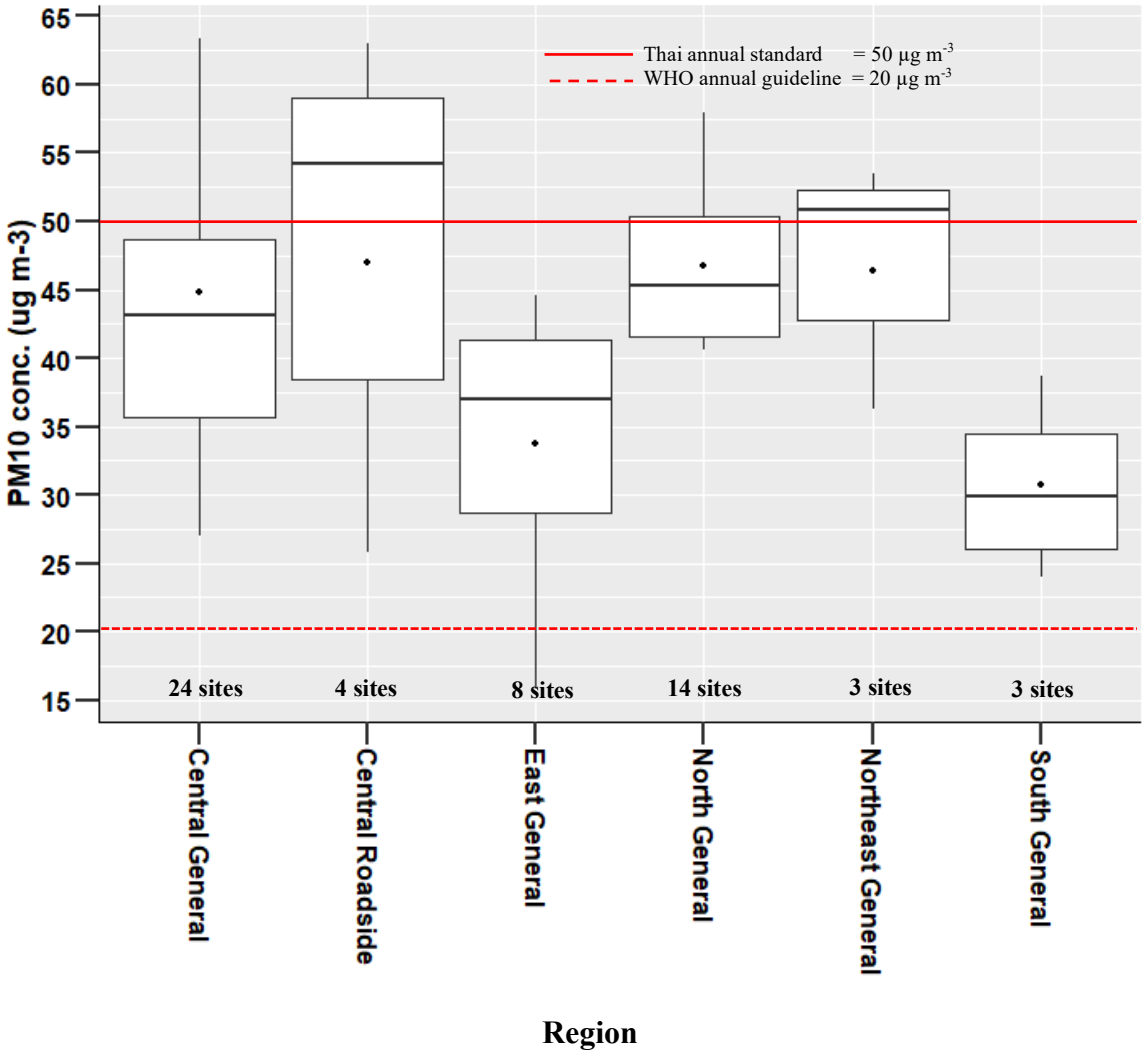



**Figure 3.5:** Comparison of annual average $PM_{10}$ concentrations between general and roadside sites across Thailand between 2011 and 2015. The bottom of the box is 25$^{th}$ percentile, the top of the box is 75$^{th}$ percentile, the whiskers show the 5$^{th}$ and 95$^{th}$ percentile, the line is the median and the dot is the mean across all sites in each region

## 3.3.2 Conditions producing annual average concentrations

### 3.3.2.1 Northern Thailand

The conditions producing annual average $PM_{10}$ concentrations were analysed using a combination of measurement data and air mass back trajectories at different locations focused on sites with the most complete data capture in each of the site categories (see methods for selection criteria as shown in appendix, Tables S3 and S4). In Northern Thailand, Chiang Mai (ID 32 and ID 33), Chiang Rai (ID 30) and Lamphun (ID 46) have the monitoring sites which met data capture criteria in different years between 2011 and 2015. Chiang Mai is a major city, and has the monitoring site (Site ID 32) which met data capture criteria in every year between 2011 and 2015. This site is a general site located in an urban, residential area. Site 32, located in Chiang Mai, Northern Thailand, had sufficient data capture in the largest number of years (5 years), and was therefore the primary site used to explore the conditions that resulted in lower annual $PM_{10}$ concentrations in this region in 2011 compared to 2012-2015. Figure 3.6 contrasts the contribution to annual average concentrations from different hourly $PM_{10}$ concentrations, months of the year, hours of the day, and air mass pathways in 2011 and 2012. Data for 2012 is representative of the period 2012 to 2015 that have the similar contributions of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ observed at Site 32 (See Table 3.1). For example, the 95$^{th}$ percentile $PM_{10}$ concentrations varied between 109 and 123 µg m$^{-3}$ between 2012 and 2015, and hourly $PM_{10}$ concentrations above the 95$^{th}$ percentile contributed 16-18% of annual average $PM_{10}$. In contrast, in 2011, the 95$^{th}$ percentile concentration was 77 µg m$^{-3}$ and hourly $PM_{10}$ concentrations above this contributed 13% to the annual average (Table 3.1).

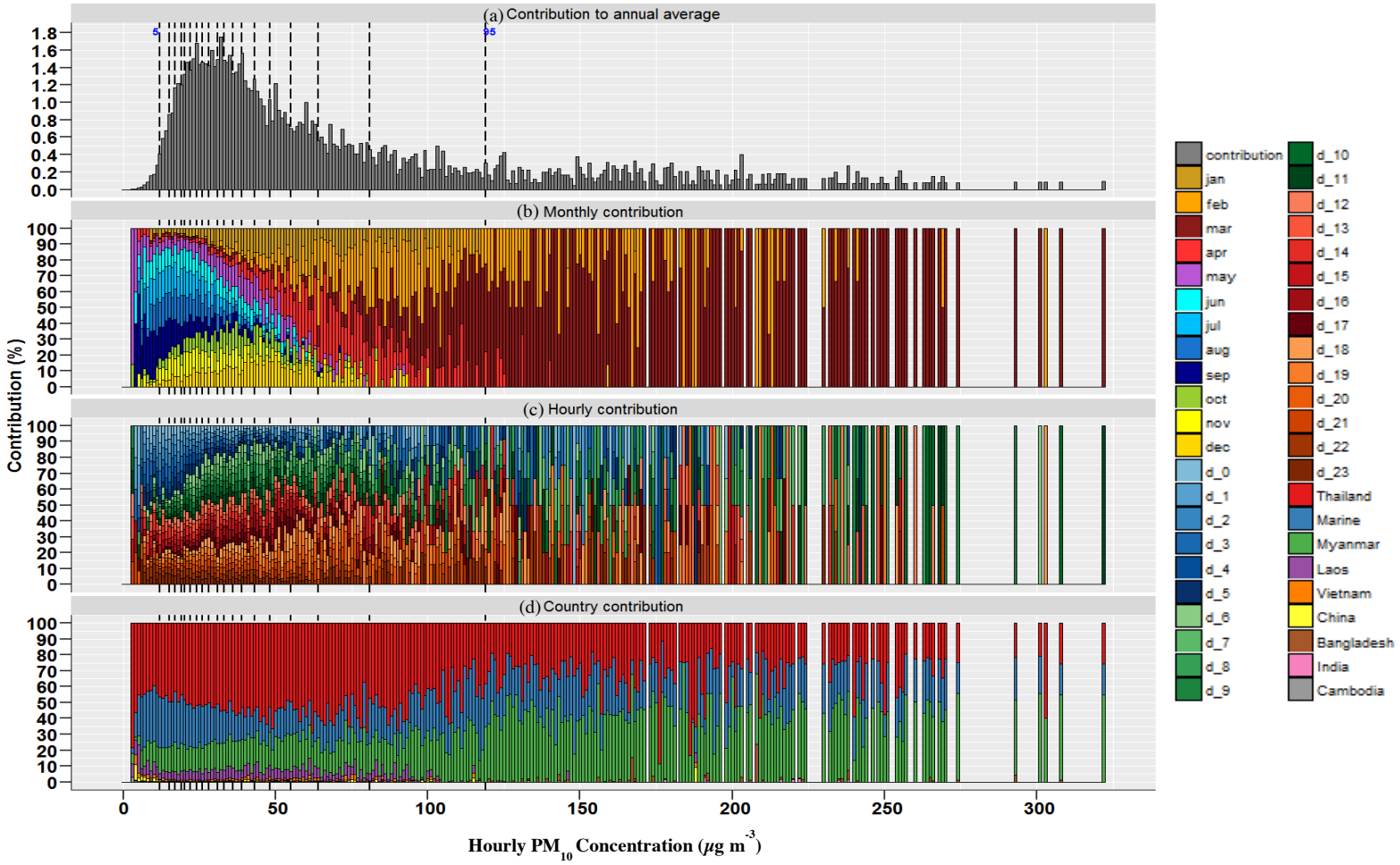



**Figure 3.6:** (a) The contribution of each hourly 1 µg $m^{-3}$ $PM_{10}$ concentration bin to the annual average $PM_{10}$ concentration, (b) The proportion of concentrations in each 1 µg $m^{-3}$ hourly $PM_{10}$ concentration bin that occurred in each month of the year, (c) The proportion of concentrations in each 1 µg $m^{-3}$ bin that occurred during each hour of the day and (d) The proportion of time back trajectories spent over different countries in the 4 days prior to arrival at site 32, Chiang Mai in 2012

Hourly $PM_{10}$ concentrations measured at site 32 were divided into 1 μg $m^{-3}$ bins, and the contribution of each hourly $PM_{10}$ concentration bin to the annual average $PM_{10}$ concentration was calculated (Figure 3.6a). In 2012, hourly $PM_{10}$ concentrations were as high as 300 μg $m^{-3}$ and the 'very high' $PM_{10}$ concentrations above the 95$^{th}$ percentile (119 μg $m^{-3}$) contributed 17% to the $PM_{10}$ annual average. These very high $PM_{10}$ concentrations occurred primarily in March (79% of the very high hourly $PM_{10}$ concentrations occurred in March), and almost exclusively during the summer season (100% occurred between February and April) (Figure 3.6b). There was a less distinct pattern of when hourly $PM_{10}$ concentrations in each bin occurred throughout the day, but the lowest hourly $PM_{10}$ concentrations generally occurred at night time (Figure 3.6c). Finally, in 2012, the 4-day back trajectory air masses that arrived during the very high concentrations spent on average 42% of the time over Myanmar before they arrived at this site, and most of the rest of the time over Thailand (32%) and the ocean (25%). Figure 3.7 shows that in March, air masses from the North were associated with the highest hourly $PM_{10}$ concentrations during this month. The colour of each line is the hourly $PM_{10}$ concentration during the hour when the trajectory arrives (grey lines represent back trajectories associated with hours when no data was measured that site).

**Table 3.1:** Comparison of the main conditions producing annual average concentrations at monitoring sites in Northern Thailand in the years between 2011 and 2015 when data capture was sufficient at each site (see methods section for data capture criteria)

| Site ID | Province | Year | Very high $PM_{10}$ concentration site conditions | | Month (%) | | | Country (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 95th Percentile concentrations (µg $m^{-3}$) | Contribution of hourly $PM_{10}$ concentrations above 95th Percentile to annual average $PM_{10}$ (%) | Feb | Mar | Apr | Myanmar | Thailand | Marine |
| **32** | Chiang Mai | 2011 | 77 | 13 | 30 | 26 | 18 | 29 | 40 | 24 |
| | | 2012 | 119 | 17 | 20 | 79 | 1 | 42 | 32 | 25 |
| | | 2013 | 109 | 16 | 3 | 76 | 20 | 31 | 27 | 42 |
| | | 2014 | 123 | 16 | 4 | 75 | 17 | 25 | 47 | 25 |
| | | 2015 | 119 | 18 | 8 | 81 | 8 | 36 | 43 | 17 |
| **33** | Chiang Mai | 2011 | 80 | 12 | 22 | 32 | 25 | 30 | 41 | 26 |
| | | 2013 | 131 | 16 | 3 | 69 | 27 | 28 | 27 | 44 |
| | | 2015 | 124 | 16 | 4 | 88 | 6 | 36 | 44 | 17 |
| **30** | Chiang Rai | 2011 | 86 | 12 | 15 | 22 | 37 | 13 | 55 | 12 |
| | | 2012 | 177 | 19 | 20 | 80 | 0 | 45 | 31 | 21 |
| | | 2014 | 124 | 17 | 0 | 76 | 21 | 25 | 47 | 17 |
| **46** | Lamphun | 2011 | 89 | 13 | 39 | 21 | 9 | 24 | 41 | 20 |
| | | 2012 | 141 | 17 | 53 | 45 | 1 | 41 | 40 | 15 |
| | | 2013 | 116 | 15 | 5 | 82 | 6 | 31 | 36 | 31 |
| | | 2014 | 115 | 14 | 7 | 66 | 15 | 20 | 52 | 24 |

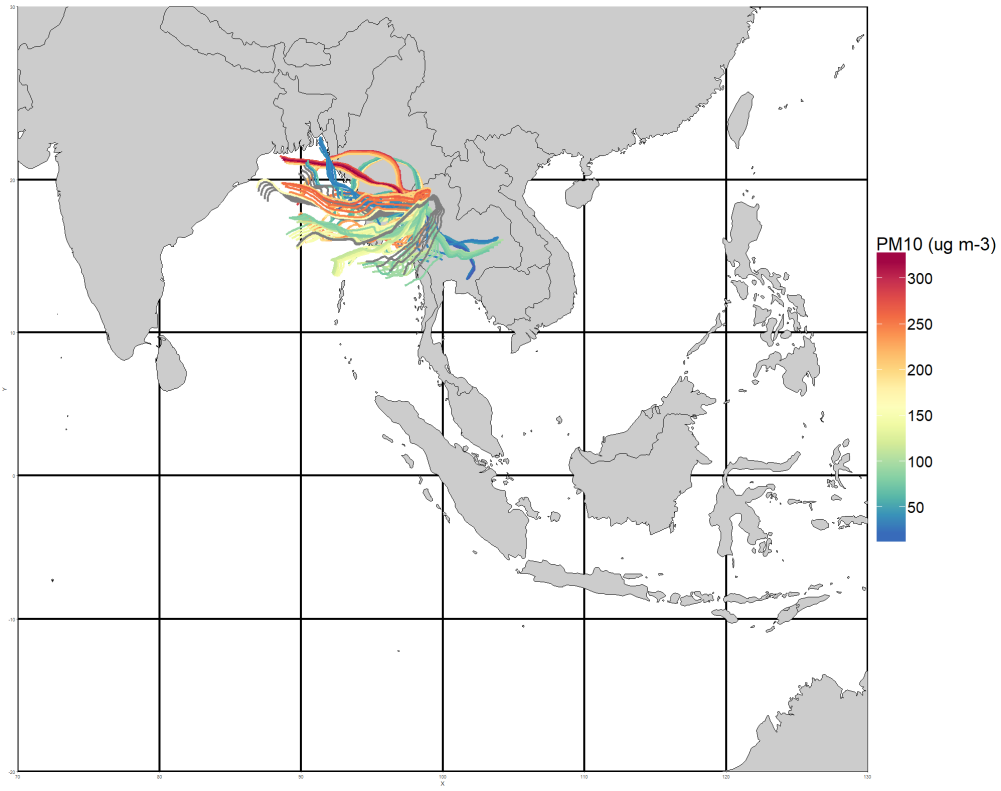



**Figure 3.7:** Air mass back trajectories arriving at Chiang Mai site (ID 32) for each day in March 2012. The colour of each line is the hourly $PM_{10}$ concentration during the hour when the trajectory *arrives* (grey lines represent back trajectories associated with hours when no data was measured that site).

In contrast, in 2011, the very high hourly $PM_{10}$ concentrations at the 95$^{th}$ percentile were much lower than 2012, only 77 µg m$^{-3}$ (compared to 119 µg m$^{-3}$ in 2012) and contributed less to the annual average, only 13% (compared to 17%) (Figure 3.8). The maximum concentrations peaked at approximately 180 µg m$^{-3}$, rather than 300 µg m$^{-3}$ in 2012. The very high concentrations at the 95$^{th}$ percentile in 2011 also did not just occur in March (26% of $PM_{10}$ concentrations above the 95$^{th}$ percentile compared to 79% in 2012) but occurred in other months across the year as shown in Table 3.1 and Figure 3.8. The back trajectories showed that during very high hourly $PM_{10}$ concentrations in 2011, air masses still spent a substantial amount of time over Myanmar prior to arrival at the site (29% of the time), but less time than in 2012 (Figure 3.9). In 2011 these air masses also spent time over Thailand (40%), the ocean (24%), as well as Laos (3%), Bangladesh (1%), Vietnam (1%), China (0.9%), India (0.3%) and Cambodia (0.1%) as shown in Table 3.1, Figure 3.8 and Figure 3.9.

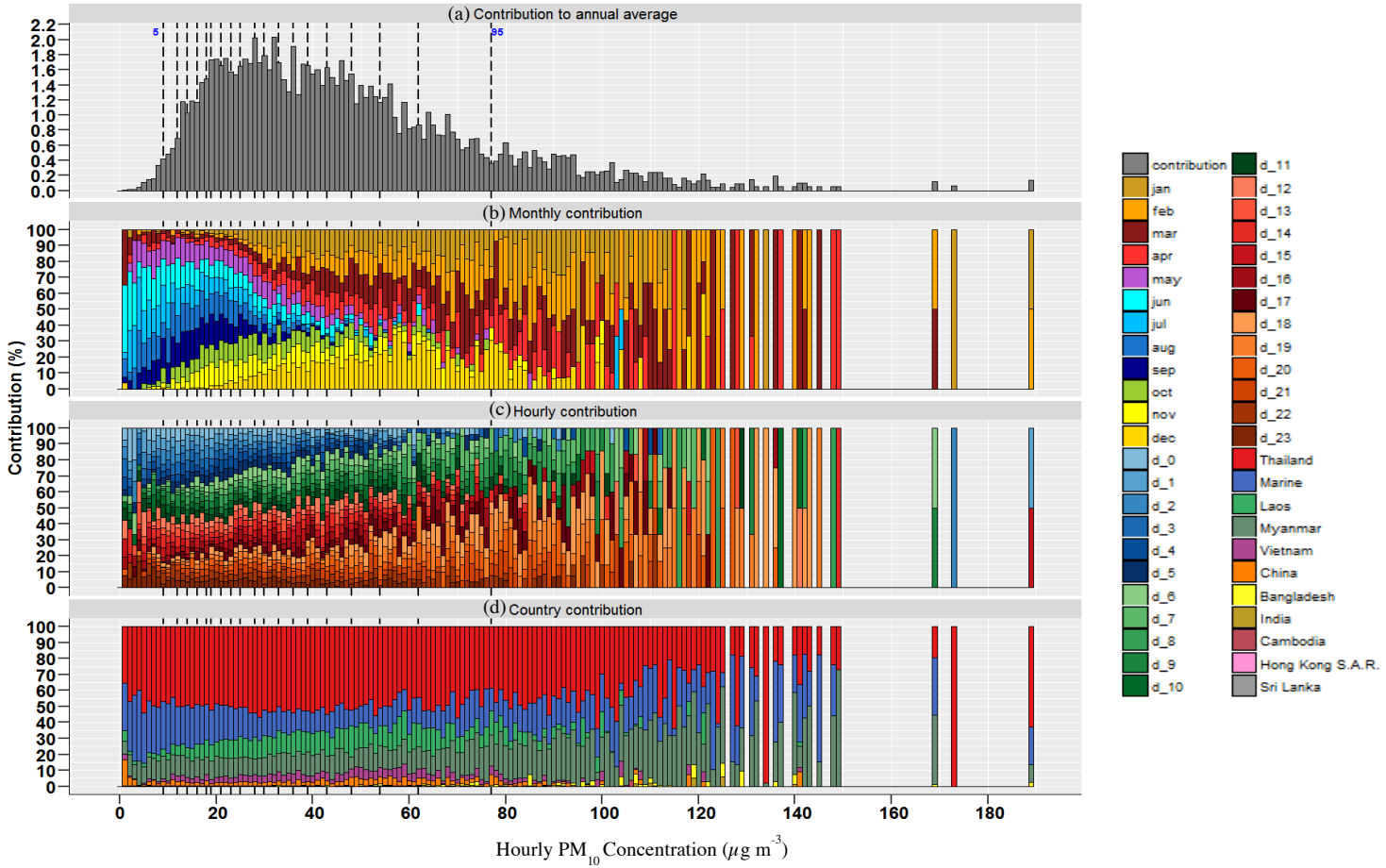



**Figure 3.8:** (a) The contribution of each hourly $PM_{10}$ concentration bin to the annual average $PM_{10}$ concentration, (b) The proportion of concentrations in each 1 µg $m^{-3}$ hourly $PM_{10}$ concentration bin that occurred in each month of the year, (c) The proportion of concentrations in each 1 µg $m^{-3}$ bin that occurred during each hour of the day and (d) The proportion of time back trajectories spent over different countries in the 4 days prior to arrival at site 32, Chiang Mai in 2011

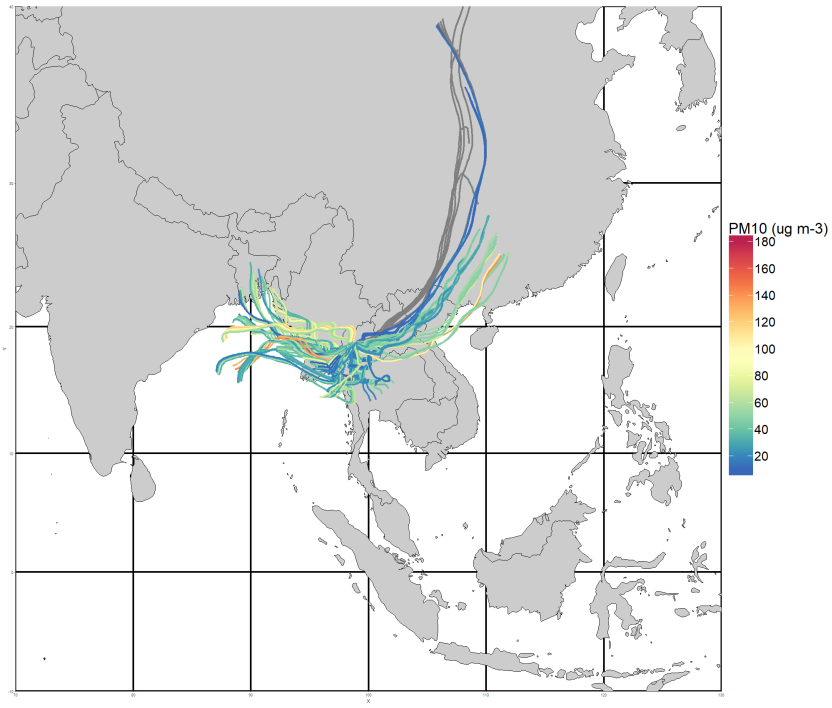



**Figure 3.9:** Air mass back trajectories arriving *at Chiang Mai site (ID 32) in March 2011.* The colour of each line is the hourly $PM_{10}$ concentration during the hour when the trajectory *arrives* (grey lines represent back trajectories associated with hours when no data was measured that site).

In summary, in 2012 at an urban general site in Chiang Mai, Northern Thailand annual average $PM_{10}$ resulted from a relatively large contribution (17%) from highest 5% of hourly $PM_{10}$ concentrations (above 119 µg $m^{-3}$). These highest hourly $PM_{10}$ concentrations generally occurred in one month (March). During these highest concentrations in March, air masses spent a substantial fraction of time over Myanmar and Thailand before arriving at the site. In contrast, the very different conditions producing annual average $PM_{10}$ concentrations in 2011 compared to the other years include lower values of the highest $PM_{10}$ concentrations in 2011, which make a smaller contribution to the annual average, and do not occur during a specific month. The highest hourly $PM_{10}$ concentrations during 2011 also spent less time over Myanmar compared to other years. Other sites in Northern Thailand with sufficient data capture to assess differences in the conditions producing annual $PM_{10}$ concentrations in 2011 and other years showed similar patterns to those at the general site in Chiang Mai (Site 32). For other sites in Northern Thailand, 2011, 2012 and 2015, the similarity of patterns identified to those at Site 32 are highlighted in Table 3.1, and in supplementary information (Appendix; Tables S5 – S7). This includes Site 33, in Chiang Mai (which had sufficient data capture in 2011, 2013 and 2015), Site 30, in Chiang Rai (2011, 2012 and 2014), and Site 46, Lamphun 2011, 2012, 2013 and 2014).

### 3.3.2.2 Southern Thailand

The conditions producing annual average $PM_{10}$ concentrations at the three locations meeting the data selection criteria (see methods) in Southern Thailand were as follows. Site 72, in Narathiwat, is a general site located in an urban area. The conditions producing annual average $PM_{10}$ concentrations in 2015 varied as shown in Figure 3.10 and Table 3.2. At Site 72, the very high concentrations above the 95$^{th}$ percentile (70 μg m$^{-3}$) contributed 13% to the $PM_{10}$ annual average in 2015, a lower percentage than at all the sites in northern Thailand. The very high concentrations occurred mainly during October (52%), September (15%) and December (14%). The moderate concentrations occurred in multiple months across the year as shown in Table 3.2. However, there was less variation across the hours of the day for very high and moderate $PM_{10}$ concentrations. The 4-day back trajectory analysis showed that the moderate concentrations spent most of the time (66%) over the ocean before arriving at this site followed by Malaysia (21%) and Thailand (10%). In contrast, the very high concentrations spent more time over Malaysia (41%) and Thailand (14%), but less time over the ocean (36%) (see Appendix, Tables S8 – S10). The substantial time spent over the ocean for moderate hourly $PM_{10}$ concentrations indicates that natural emissions, such as sea salt, or anthropogenic shipping emissions may make a contribution to these moderate concentrations, while for higher hourly $PM_{10}$ concentrations, the less time spent over the ocean indicates a greater contribution from anthropogenic, land-based emissions (which may also include other natural sources on land, such as natural secondary organic aerosol formation). The composition of $PM_{10}$ was not measured at the measurement sites, which could provide substantially greater insight into the sources of hourly $PM_{10}$ in different concentrations bin (see for example Malley et al. 2016), by providing the contribution of, chloride and sodium ions to overall $PM_{10}$ concentrations to indicate the contribution of sea salt.

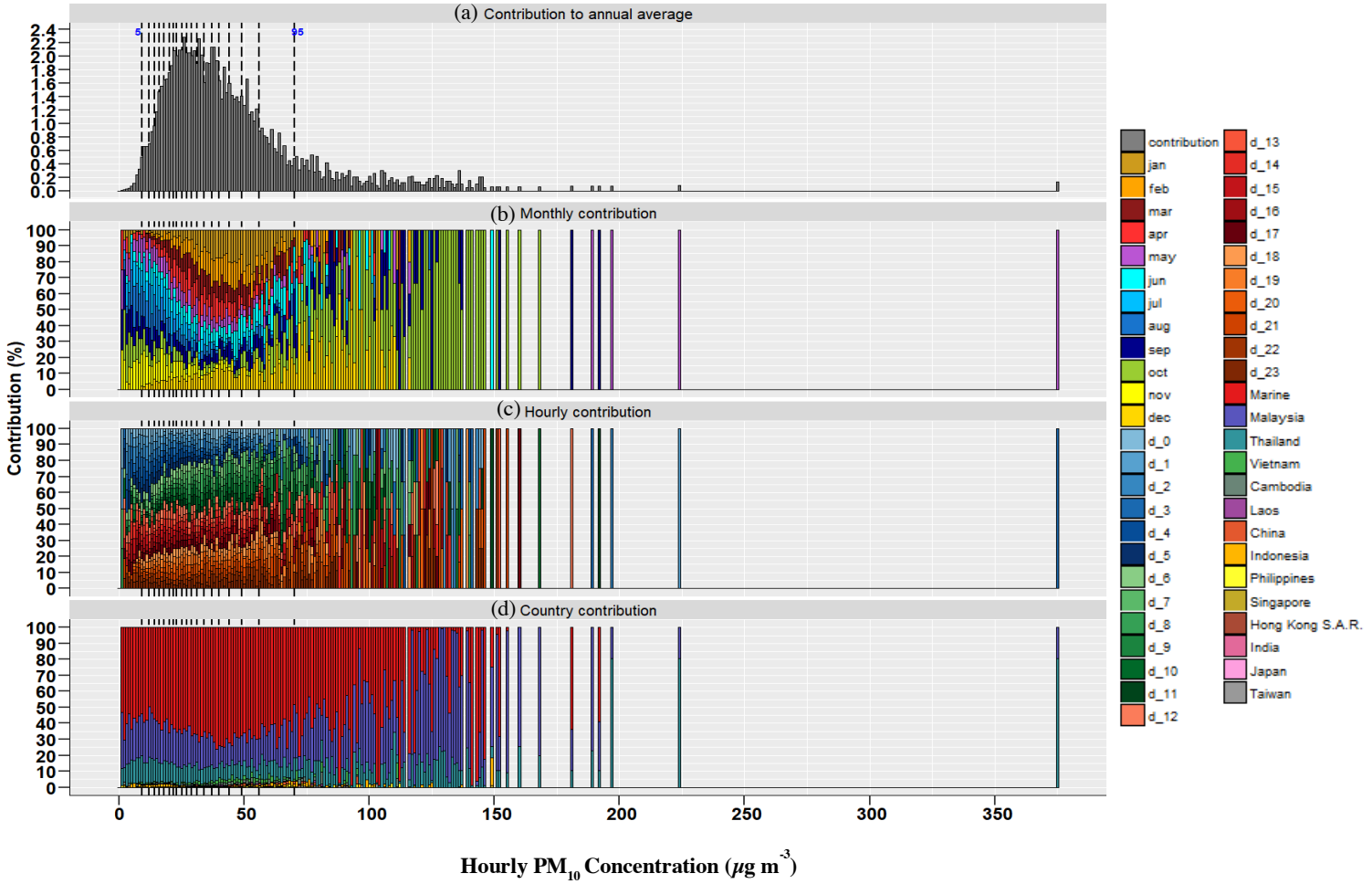



**Figure 3.10:** The different conditions producing annual average $PM_{10}$ concentrations at site 72, Narathiwat in 2015

**Table 3.2:** Comparison of the main conditions producing annual average concentrations at monitoring sites in Southern Thailand in different years and months

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Narathiwat (Site 72) | General site | 2015 | Very Low | <5th Percentile | 9 | 1 | 4 | 11 | 13 | 17 | 17 | 16 | 0.5 |
| | | | Low | <25th Percentile | 18 | 8 | 5 | 13 | 16 | 13 | 13 | 16 | 2 |
| | | | Moderate | 25th -75th Percentile | 18-40 | 37 | 8 | 8 | 7 | 6 | 5 | 7 | 8 |
| | | | High | >75th Percentile | 40 | 41 | 7 | 1 | 2 | 14 | 41 | 1 | 14 |
| | | | Very High | >95th Percentile | 70 | 13 | 5 | 0.2 | 1 | 15 | 52 | 0.2 | 14 |
| | | 2010 | Very Low | <5th Percentile | 13 | 1 | 19 | 7 | 3 | 8 | 5 | 20 | 11 |
| | | | Low | <25th Percentile | 20 | 12 | 16 | 10 | 7 | 9 | 6 | 17 | 10 |
| | | | Moderate | 25th -75th Percentile | 20-33 | 40 | 8 | 8 | 9 | 10 | 10 | 6 | 6 |
| | | | High | >75th Percentile | 33 | 37 | 4 | 4 | 6 | 4 | 9 | 3 | 20 |
| | | | Very High | >95th Percentile | 49 | 10 | 3 | 3 | 5 | 4 | 9 | 2 | 23 |
| Phuket (Site 73) | General site | 2013 | Very Low | <5th Percentile | 8 | 1 | 14 | 2 | 3 | 19 | 11 | 14 | - |
| | | | Low | <25th Percentile | 15 | 9 | 11 | 4 | 6 | 16 | 14 | 14 | 1 |
| | | | Moderate | 25th -75th Percentile | 15-30 | 40 | 6 | 10 | 12 | 10 | 8 | 7 | 5 |
| | | | High | >75th Percentile | 30 | 39 | 26 | 4 | 3 | 0.3 | 8 | 2 | 18 |
| | | | Very High | >95th Percentile | 46 | 11 | 31 | 2 | 2 | - | 11 | 2 | 17 |
| | | 2008 | Very Low | <5th Percentile | 11 | 1 | 5 | 6 | 7 | 8 | 23 | 41 | 1 |
| | | | Low | <25th Percentile | 19 | 10 | 7 | 8 | 8 | 10 | 16 | 27 | 1 |
| | | | Moderate | 25th -75th Percentile | 19-35 | 41 | 7 | 9 | 9 | 9 | 6 | 6 | 7 |
| | | | High | >75th Percentile | 35 | 37 | 5 | 5 | 7 | 2 | 20 | 17 | 16 |
| | | | Very High | >95th Percentile | 52 | 10 | 5 | 3 | 5 | 1 | 25 | 21 | 14 |

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Songkhla (Site 75) | General site | 2014 | Very Low | <5th Percentile | 20 | 2 | 1 | 1 | 10 | 22 | 16 | 21 | 11 |
| | | | Low | <25th Percentile | 32 | 12 | 2 | 2 | 11 | 18 | 15 | 18 | 12 |
| | | | Moderate | 25th -75th Percentile | 32-52 | 41 | 6 | 9 | 7 | 7 | 8 | 4 | 10 |
| | | | High | >75th Percentile | 52 | 36 | 22 | 24 | 7 | 4 | 3 | 3 | 5 |
| | | | Very High | >95th Percentile | 75 | 10 | 25 | 30 | 6 | 3 | 3 | 3 | 6 |
| | | 2010 | Very Low | <5th Percentile | 15 | 1 | 30 | 5 | 9 | 2 | 1 | 8 | 13 |
| | | | Low | <25th Percentile | 23 | 10 | 23 | 6 | 7 | 3 | 3 | 11 | 12 |
| | | | Moderate | 25th -75th Percentile | 23-40 | 41 | 6 | 8 | 8 | 10 | 8 | 7 | 8 |
| | | | High | >75th Percentile | 40 | 37 | 5 | 10 | 13 | 8 | 3 | 2 | 13 |
| | | | Very High | >95th Percentile | 59 | 10 | 4 | 10 | 12 | 8 | 1 | 2 | 14 |

**Table 3.3:** Comparison of the main conditions producing annual average concentrations at monitoring sites in Southern Thailand in different years and countries

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Marine | Malaysia | Thailand | Indonesia | Vietnam | Cambodia | Laos |
| **Narathiwat (Site 72)** | General site | 2015 | Very Low | <5th Percentile | 9 | 1 | 59 | 25 | 13 | 1 | 0.3 | 1 | - |
| | | | Low | <25th Percentile | 18 | 8 | 58 | 26 | 14 | 1 | 0.5 | 1 | - |
| | | | Moderate | 25th-75th Percentile | 18-40 | 37 | 66 | 21 | 10 | 1 | 1 | 1 | 0.2 |
| | | | High | >75th Percentile | 40 | 41 | 50 | 35 | 13 | 1 | 1 | 1 | 0.1 |
| | | | Very High | >95th Percentile | 70 | 13 | 43 | 41 | 14 | 1 | 0.5 | 0.3 | 0.1 |
| | | 2010 | Very Low | <5th Percentile | 13 | 1 | 62 | 21 | 12 | 1 | 3 | 0.3 | 0.1 |
| | | | Low | <25th Percentile | 20 | 12 | 58 | 23 | 14 | 1 | 3 | 1 | 0.1 |
| | | | Moderate | 25th-75th Percentile | 20-33 | 40 | 61 | 20 | 15 | 1 | 1 | 1 | 0.1 |
| | | | High | >75th Percentile | 33 | 37 | 58 | 17 | 16 | 0.4 | 4 | 2 | 1 |
| | | | Very High | >95th Percentile | 49 | 10 | 53 | 20 | 17 | 0.3 | 4 | 3 | 1 |
| **Phuket (Site 73)** | General site | 2013 | Very Low | <5th Percentile | 8 | 1 | 86 | 1 | 10 | 0.5 | 1 | 2 | 0.2 |
| | | | Low | <25th Percentile | 15 | 9 | 85 | 1 | 10 | 1 | 1 | 2 | 0.3 |
| | | | Moderate | 25th-75th Percentile | 15-30 | 40 | 83 | 1 | 10 | 2 | 2 | 2 | 0.3 |
| | | | High | >75th Percentile | 30 | 39 | 74 | 0.1 | 18 | 0.4 | 3 | 3 | 1 |
| | | | Very High | >95th Percentile | 46 | 11 | 74 | 0.1 | 18 | 0.2 | 2 | 2 | 2 |
| | | 2008 | Very Low | <5th Percentile | 11 | 1 | 76 | - | 9 | 1 | 8 | 4 | 1 |
| | | | Low | <25th Percentile | 19 | 10 | 79 | 0.1 | 10 | 1 | 5 | 3 | 1 |
| | | | Moderate | 25th-75th Percentile | 19-35 | 41 | 81 | 0.1 | 12 | 2 | 1 | 2 | 1 |
| | | | High | >75th Percentile | 35 | 37 | 71 | - | 19 | 2 | 2 | 3 | 2 |
| | | | Very High | >95th Percentile | 52 | 10 | 70 | - | 19 | 1 | 2 | 3 | 2 |

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Marine | Malaysia | Thailand | Indonesia | Vietnam | Cambodia | Laos |
| **Songkhla (Site 75)** | General site | 2014 | Very Low | <5th Percentile | 20 | 2 | 69 | 2 | 20 | 1 | 4 | 2 | 0.4 |
| | | | Low | <25th Percentile | 32 | 12 | 69 | 4 | 18 | 1 | 3 | 2 | 1 |
| | | | Moderate | 25th-75th Percentile | 32-52 | 41 | 69 | 7 | 16 | 1 | 3 | 2 | 1 |
| | | | High | >75th Percentile | 52 | 36 | 52 | 23 | 18 | 1 | 2 | 2 | 1 |
| | | | Very High | >95th Percentile | 75 | 10 | 48 | 28 | 18 | 1 | 2 | 2 | 1 |
| | | 2010 | Very Low | <5th Percentile | 15 | 1 | 70 | 6 | 18 | 1 | 2 | 1 | 0.2 |
| | | | Low | <25th Percentile | 23 | 10 | 71 | 5 | 17 | 1 | 3 | 2 | 0.3 |
| | | | Moderate | 25th-75th Percentile | 23-40 | 41 | 74 | 4 | 16 | 1 | 2 | 2 | 0.2 |
| | | | High | >75th Percentile | 40 | 37 | 60 | 9 | 22 | 1 | 4 | 2 | 1 |
| | | | Very High | >95th Percentile | 59 | 10 | 58 | 9 | 23 | 1 | 5 | 3 | 1 |

Other sites in Southern Thailand with sufficient data capture were: Site 73 (Phuket) which is a general site located in an urban area. The very high concentrations at the 95$^{th}$ percentile (46 μg m$^{-3}$) contributed 11% to the annual average concentrations in 2013 at Site 73 (Figure 3.11), while the moderate concentrations contributed 40% (Table 3.3). The moderate concentrations occurred across all months of the year, but the very high concentrations occurred disproportionately in June (31%), and December (17%), which are associated with biomass burning events in Malaysia and Indonesia (Field et al., 2016; PCD, 2015). Similarly, moderate concentrations occurred across the whole day while very high concentrations mainly occurred in the morning and evening. The majority of time was spent over the ocean prior to arrival at the site for both moderate (83%) and very high (74%) concentrations (Figure 3.12).

In summary, the effect of long-range pollution transport at this site in Phuket is lower than other sites in Southern Thailand and other regions. Air masses spend the majority of time over the ocean and less time spent over Thailand and other countries in comparison to Site 73 in southern Thailand, and the northern Thailand sites. The lower proportion of time spent over land, where emissions sources are likely to be greater, means that the 95$^{th}$ percentile value was lower at this site than others, contributed a smaller proportion of annual average $PM_{10}$ concentrations, and that the annual $PM_{10}$ concentration was lower compared with other sites.

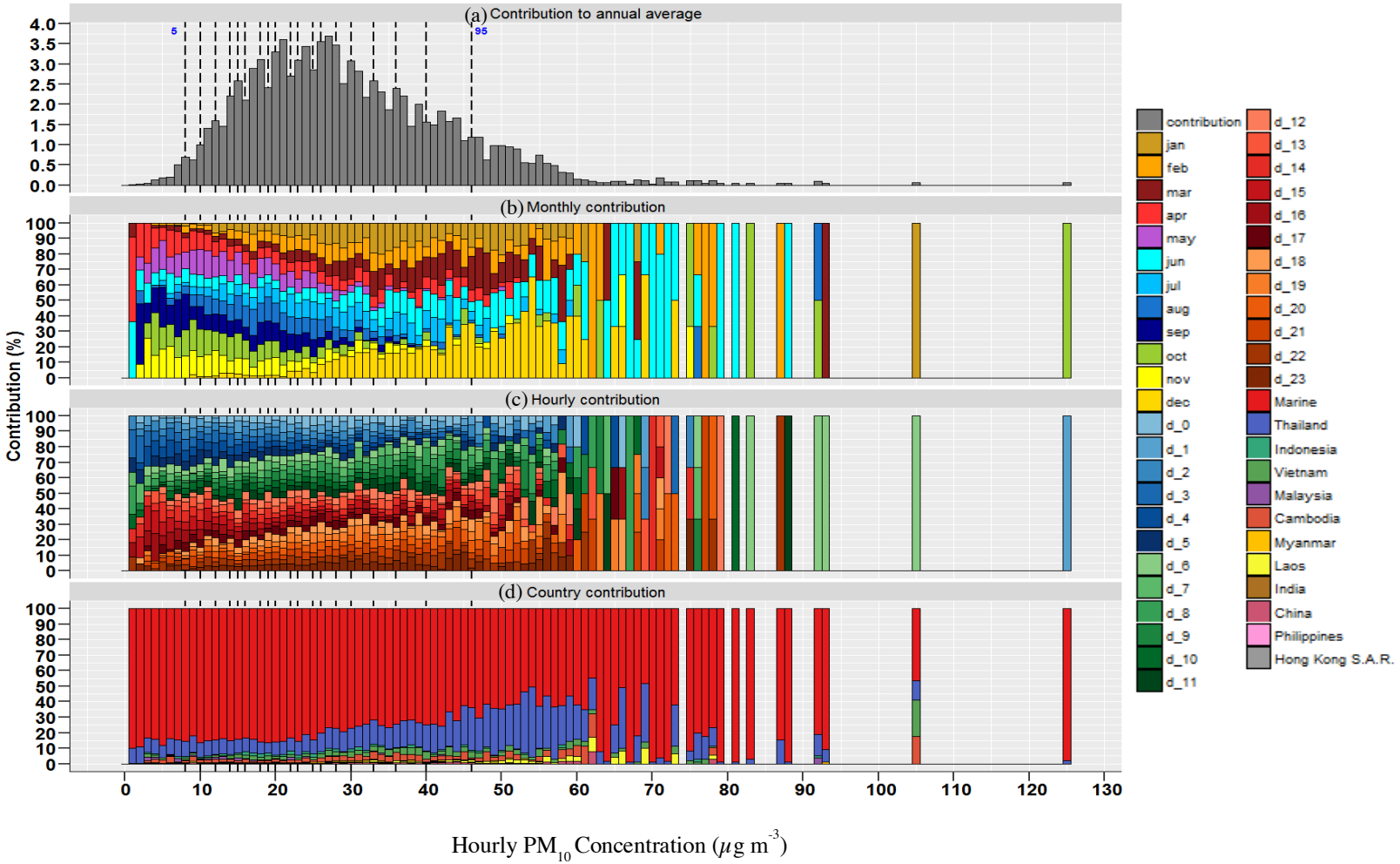



**Figure 3.11:** The different conditions producing annual average $PM_{10}$ concentrations at site 73, Phuket in 2013

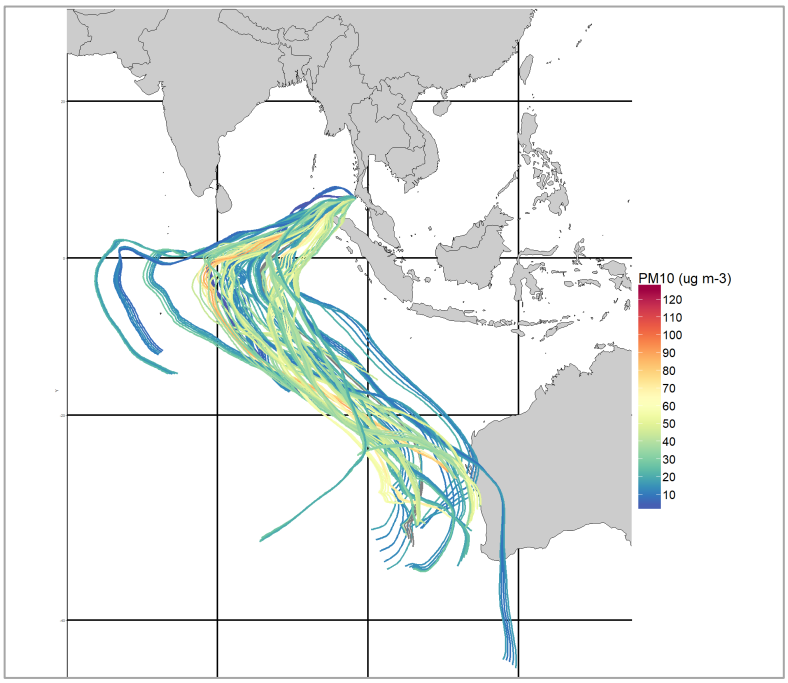



**Figure 3.12:** Air mass back trajectories arriving at Phuket site (ID 73) in June, 2013. Each line represents a back trajectory arriving at 12 pm on each day in June, and are coloured according to the hourly $PM_{10}$ concentration recorded during this hour (The colour of each line is the hourly $PM_{10}$ concentration during the hour when the trajectory arrives (grey lines represent back trajectories associated with hours when no data was measured that site).

The last site with sufficient data capture in Southern Thailand is Songkhla site (ID 75) which is a general site located in an urban area as well. In 2014, the very high concentrations (above 95$^{th}$ percentile (75 µg m$^{-3}$)) contributed 10% to annual average $PM_{10}$ (Figure 3.13). These highest hourly $PM_{10}$ concentrations occurred mostly in July (30%) and June (25%), and at night and in the evening. The air masses associated with these highest hourly $PM_{10}$ concentrations spent less time over marine 48%, and more time over Malaysia 28% and Thailand 18% compared to lower hourly $PM_{10}$ concentrations. In contrast, the moderate concentrations contributed 41% to the annual average and occurred in multiple months across the year, across the whole day, and air masses spent most of time over marine (69%), Thailand (16%) and Malaysia (7%) as shown in Table 3.2, Table 3.3 and Figure 3.14.

In summary, the effect of long rang transport at site 75, in Songkhla is similar to site 72, Narathiwat. Air masses spent the majority of time over the ocean and Malaysia and spent less time over land, contributed a smaller proportion of annual average $PM_{10}$ concentrations, and that the annual $PM_{10}$ concentration was also lower compared with other sites.

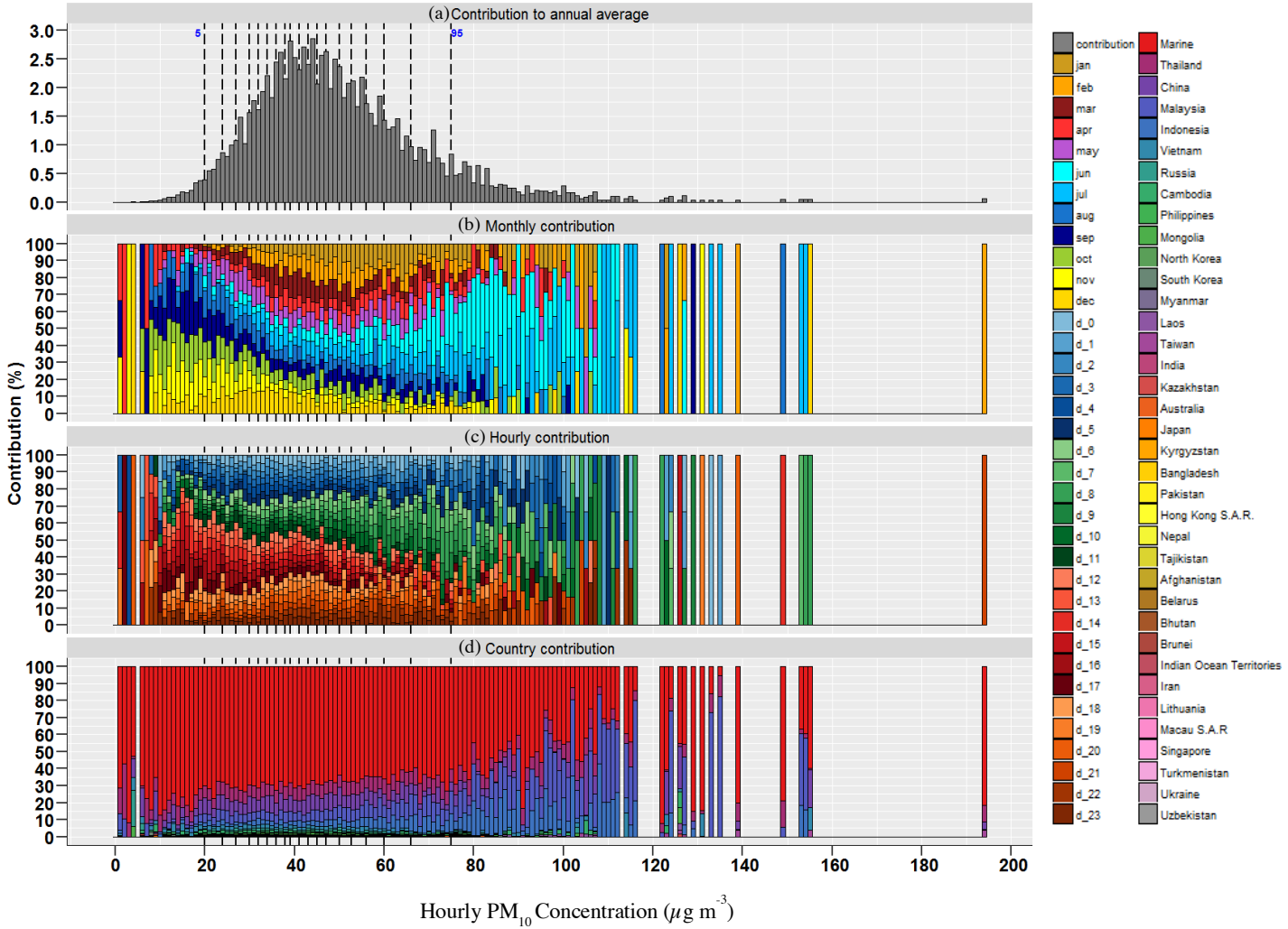
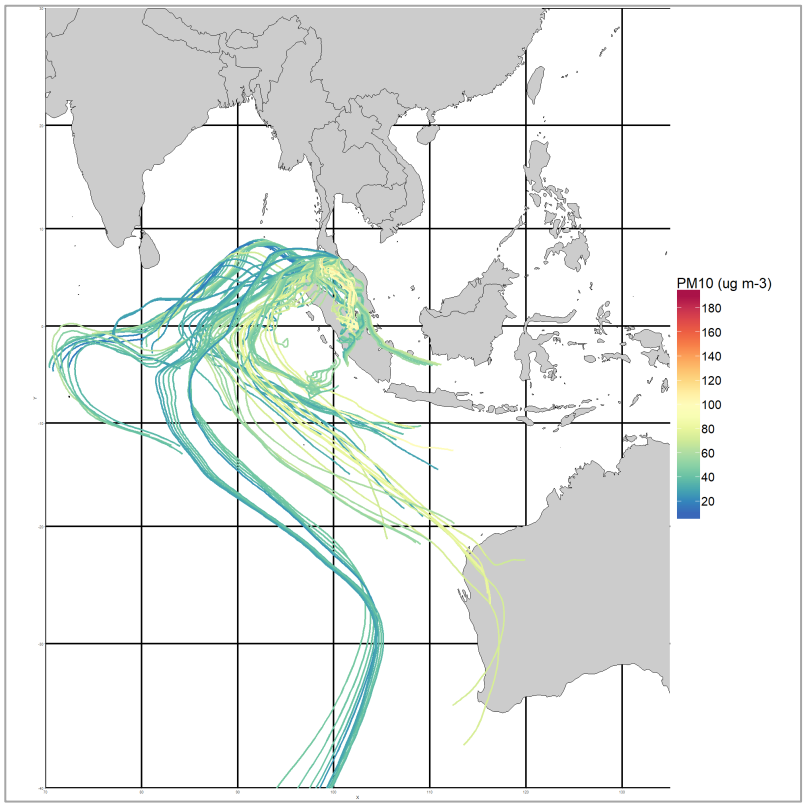



**Figure 3.13:** The different conditions producing annual average $PM_{10}$ concentrations at site 75, Songkhla in 2014

(a) June




(b) July

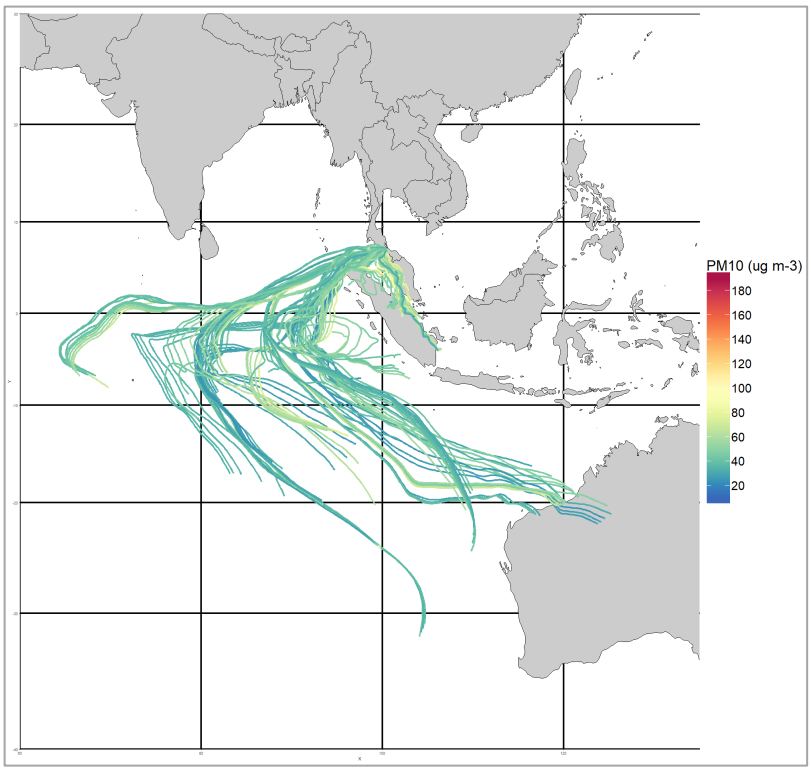



**Figure 3.14:** Backward air masses trajectory plots at Songkhla site (ID 75) in (a) June and (b) July, 2014

In June (a) and July (b) in 2014, the back trajectories showed air masses transport from southerly directions, covering from Malaysia, Singapore, Indonesia, Thailand and the ocean as shown in Figure 3.14.

In 2010, the very high concentrations at the 95$^{th}$ percentile (59 μg m$^{-3}$) contributed 10% to the annual average as shown in Table 3.2 and Table 3.3. The moderate concentrations contributed 41% to the annual average. The very high concentrations mainly occurred in January (17%) and December (14%). In contrast, the moderate concentrations occurred across the whole year which is the same pattern as observed at Site 73 in Phuket in 2008. The moderate concentrations of air masses spent most of the time over marine 74% and Thailand 17%. However, the very high concentrations spent less time over marine 58%, and more time over Thailand (23%).

In summary, across the three sites in southern Thailand there was variation in contribution from long-range transport in producing annual average $PM_{10}$ concentrations, but at all sites this contribution was lower than at sites in northern Thailand. At Site 72, Narathiwat, that appeared to have the largest contribution from long-range transport, very high hourly $PM_{10}$ concentrations were associated with specific months, and the transport of southerly air masses to the site, traversing Malaysia and Indonesia prior to their arrival. However, the magnitude of the very high hourly $PM_{10}$ concentrations associated with these conditions were lower than at sites in northern Thailand, and also made a smaller contribution to annual $PM_{10}$ concentrations at this site compared to sites in northern Thailand. Other sites in southern Thailand were further from neighbouring countries, and surrounded by ocean, and the very high hourly $PM_{10}$ concentrations at these sites were less associated with increases in the time trajectories spent over neighbouring countries, and made even smaller contributions to the annual average $PM_{10}$ concentration.

## 3.4. Discussion

### 3.4.1 Implications for annual $PM_{10}$ concentrations in Northern and Southern Thailand

In this study, data from the Thailand national air pollution monitoring network has been used to investigate the contribution of biomass burning periods to determining the magnitude of annual average $PM_{10}$ concentrations in northern and southern Thailand. The key findings from this study are that between 2012 and 2015 (non-La Nina years), in northern Thailand, the average 2012-2015 annual $PM_{10}$ concentration consistently exceeded the 50 $\mu g\ m^{-3}$ standard at multiple sites. While the majority of annual average $PM_{10}$ was determined by relatively frequent, moderate hourly $PM_{10}$ concentrations (20-80 $\mu g\ m^{-3}$), relatively high hourly $PM_{10}$ concentrations also made a substantial contribution (15-20% > 120 $\mu g\ m^{-3}$), and these mainly occurred during March. In 2011, a La Nina year, the number of high hourly $PM_{10}$ concentrations that occurred in March was substantially lower than between 2012 and 2015, and consequently the annual $PM_{10}$ concentrations at all sites in northern Thailand did not exceed the 50 $\mu g\ m^{-3}$ national standard. In southern Thailand, there were substantially fewer monitoring sites, but for those sites that were available, the results showed that the annual average $PM_{10}$ concentrations for individual years between 2011 and 2015 did not exceed the 50 $\mu g\ m^{-3}$ annual $PM_{10}$ standard at any site. The frequency of high hourly $PM_{10}$ concentrations (i.e. > 120 $\mu g\ m^{-3}$), was much less than for sites in northern Thailand. The peak concentrations at sites in southern Thailand generally occurred in October and were associated with transport of southerly air masses towards Thailand. However, in terms of the WHO guideline annual average of 20 $\mu g\ m^{-3}$ for $PM_{10}$ there was widespread exceedance of this value in most years in southern and northern Thailand. This result is in line with the fact that in 2016, 91% of the world population was living in places where the WHO air quality guidelines levels were not met (WHO, 2018).

The PCD has highlighted previously the role of long-range transport and biomass burning in producing short-term peak $PM_{10}$ episodes across Thailand (PCD, 2015; PCD, 2018). In addition to the trapping of locally emitted pollutants due to weather conditions such as temperature inversions, the PCD (2016) noted that elevated air pollution in northern Thailand originates from forest fires and agricultural open burning both locally (i.e. within Thailand) and through transboundary transport from neighbouring countries between January and April. This is consistent with the results presented in this Chapter

that show the trajectory of air masses with highest hourly $PM_{10}$ concentrations occurring in dry season and also related to biomass burning in Thailand and in neighbouring countries. High $PM_{10}$ concentrations were previously linked with biomass burning activities in pre-monsoon season (March - April) (Janjai et al., 2009). In contrast, in southern Thailand, high peak $PM_{10}$ concentrations typically occur between June and October. This is consistent with the timing of agricultural and deforestation burning practices in Indonesia that have been shown to produce transboundary haze affecting Thailand and other south-east Asian countries (Field et al., 2016; PCD, 2016; Koe et al., 2001; Thompson et al., 2001). Other potential emission sources that could contribute to the highest hourly $PM_{10}$ concentrations in southern Thailand, such as shipping emissions, or local activities do not display the same seasonality in emission source strengths.

Other recent studies also identified biomass burning as a major source of high hourly $PM_{10}$ concentrations. Punsompong and Chantara (2018) showed for one monitoring site in Chiang Mai in northern Thailand between 2010 and 2015 that high $PM_{10}$ concentrations mainly occurred in dry season during February to April. Based on potential source contribution function analysis of air mass back trajectories, they estimated that during this period the contribution to hourly $PM_{10}$ concentrations from Myanmar was 73% and from Thailand was 27%. In Myanmar, the major high-potential sources were open agricultural burning, followed by forest burning, and in Thailand, the major contribution was from agricultural burning. Kim Oahn and Leelasakultum (2011) identified that the highest 24-hr $PM_{10}$ concentrations in Chiang Mai occurred during March in 2007, and air mass back trajectories on haze episode days had passed over regions of dense biomass fire hotspots before arriving in Chiang Mai. Other previous studies have also highlighted the role of biomass burning in northern Thailand, Myanmar, and other Southeast Asian countries to short-term peaks in $PM_{10}$ concentrations (Phayungwiwatthanakoon, 2013; PCD, 2010b; PCD 2012).

The results in this study are consistent with those presented previously on the major contribution of biomass burning emissions to the highest hourly $PM_{10}$ concentrations in Northern Thailand. However, this study extends the analyses to show that this source not only contributes to short-term peak $PM_{10}$ concentrations in northern Thailand, but that these high hourly $PM_{10}$ concentrations that occur during the relatively short biomass burning period in northern Thailand, make a substantial contribution, in the order of 15-20%, to annual $PM_{10}$ concentrations in this region.

In addition, the analysis here indicates that reduction of the high hourly $PM_{10}$ concentrations that occur during the biomass burning period in northern Thailand could lead to all sites in northern Thailand meeting the Thai ambient air quality standard for annual $PM_{10}$ concentrations. For example, in 2011, there was a consistent decrease in annual average $PM_{10}$ concentrations compared to normal years at all sites across northern Thailand. Huang *et al.* (2016) investigated biomass burning using satellite observations over Myanmar and northern Thailand. The result showed that the amount of biomass burned in 2011 was less than a quarter of the biomass burning in 2012, 2013, 2014 and 2015, due to the La Nina conditions in 2011. Therefore, biomass burning was substantially lower in Myanmar and northern Thailand in 2011. This was attributed to anomalously high premonsoon rainfall in the region in March 2011 (Hunag et al, 2016). The results presented here show that this resulted in fewer very high $PM_{10}$ concentrations during Thailand's summer period, and consequently much lower annual average $PM_{10}$ concentrations across all sites in northern Thailand in 2011, and no exceedances of the Thailand $PM_{10}$ standard. Another study showed the absence of haze episodes during January to April 2011 and indicated that this was related to the reduction in number of fire hotspots, the amount of precipitation, and the wind circulation, all of which contributed to the lower $PM_{10}$ concentrations in 2011 in northern Thailand (Sooktawee, Mongkut and Tho, 2015).

The results presented here emphasise the substantial benefits that could result from reducing the extent of crop residue and forest fire burning both in Thailand and Myanmar in terms of reducing long-term (annual average) exposure to PM in northern Thailand, in addition to reducing short-term peak episodes. As stated in the introduction, annual average exposure to $PM_{10}$ (and $PM_{2.5}$, which is highly correlated) has a substantially higher impact on human health than short-term peak exposures (WHO, 2013). Therefore, this suggests that human health benefits from reductions in air pollution can be enhanced by strategically reducing the pollution sources causing long-term (i.e. annual) PM concentrations. This study shows that in northern Thailand, a key strategy for achieving this is focusing on the minimisation of emissions from crop residue and forest fire burning during a particular time of the year. During the year of this analysis in which emissions from biomass burning in northern Thailand were shown previously to have been substantially lower (2011), no monitoring sites in northern Thailand exceeded the Thai

national standard for annual average $PM_{10}$. This was not achieved in any other year where biomass burning emissions were elevated during March.

In southern Thailand, in common with northern Thailand sites, the analysis presented here indicates that a main source of high peak $PM_{10}$ concentrations was long-range transport from biomass burning, but that the frequency of high hourly $PM_{10}$ concentrations from this source was substantially less than in northern Thailand. This is consistent with previous work that showed $PM_{10}$ concentrations tended to increase in southern Thailand during June to October due to forest fires in Sumatra and Borneo in Indonesia (PCD, 2015). While the number of years available for analysis at sites in southern Thailand was lower than in northern Thailand, $PM_{10}$ episodes have been shown to occur in other years (Tangang, 2010). Haze in Southeast Asia region has been mainly attributed to the long-range transport of pollutants from biomass fires in Sumatra and the Kalimantan on Borneo Island, Indonesia (Radojevic and Hassan, 1999). However, the results from this study show that although reducing the high hourly $PM_{10}$ concentrations in southern Thailand, that occur during the biomass burning period could, reduce short-term peak $PM_{10}$ concentrations, it would have a very limited effect in reducing the annual average $PM_{10}$ concentration in this region, e.g. to achieve the WHO air quality guidelines of 20 $\mu g\ m^{-3}$ annual mean.

In 2014, there were no days recorded where the $PM_{10}$ level exceeded the standard in southern Thailand (PCD, 2015), but in 2013, the peak period for transboundary haze occurred in June (Betha, Behera and Balasubramanian, 2014). Previous studies have also highlighted the strong control of El Niño conditions that can also have a strong control on the magnitude of the fire activity resulting from anthropogenic practices such as forest degradation, clearance activities and human-caused ignitions occurring annually across Borneo, Indonesia (Wooster et al., 2012). In October 2006, under El Niño conditions the severest fire incidents for whole Kalimantan occurred under the driest conditions in both Palangkaraya and Pontianak but only occurred in Palangkaraya in late September 2009 (Yulianti and Hayasaka, 2013). In Singapore, between August and October 2009, tropical burning, particularly in peatlands were enhanced by a moderate El Niño event (Atwood et al., 2013).

Finally, the results of this study have been obtained through the consistent calculation of a standard set of 'chemical climatology' statistics at all available sites in northern and southern Thailand. The aim of these statistics, and the chemical climatology framework, is to increase the information derived from monitoring networks beyond the assessment of the magnitude of a particular regulatory metric, and whether the monitoring sites are in compliance with national ambient air quality standards or international air quality guidelines. This has been achieved by calculating additional statistics that were specifically defined to determine how variation in hourly $PM_{10}$ concentrations determines a specific impact metric (annual $PM_{10}$ concentrations). These additional statistics highlighted the contrasting situations in northern and southern Thailand, where relatively high hourly $PM_{10}$ concentrations occur during biomass burning periods in both regions. However, the implications for the annual $PM_{10}$ 'impact' metric at sites in both regions is very different. Reduction of the high hourly $PM_{10}$ concentrations during biomass burning periods in northern Thailand could be effective in reducing annual $PM_{10}$ below the Thai national standard in this region, which is equivalent to Interim Target - 2 (IT-2) of 50 $\mu g\ m^{-3}$ annual mean concentrations from WHO guidelines. In contrast, in southern Thailand, reductions in the highest hourly $PM_{10}$ concentrations would have little effect on annual $PM_{10}$ concentrations. The future application of these chemical climatology statistics to other monitoring sites in Thailand, south-east Asia, or other regions could facilitate a consistent comparison of the conditions producing annual $PM_{10}$ concentrations in different areas, and to identifying the most effective mitigation strategies to reduce them (i.e. the hours, months of the year where biomass burning makes a largest contribution to the annual $PM_{10}$ concentrations, and therefore the time period when mitigation needs to be focused and to the back trajectory analysis the geographic regions where that mitigation needs to occur). This approach can also be used to evaluate atmospheric chemistry transport models that are able to access specific mitigation measure targeting specific sources e.g. evaluated complete band on biomass burning or crop residue burning.

### 3.4.2 Uncertainties

Key limitations for this study are the small number of sites and years in southern Thailand. The results that are presented here are consistent with previous studies in this region on the contribution of long-range transport during biomass burning periods to peak $PM_{10}$ concentrations. However, as more measurements are collected at southern Thailand sites, there will be the opportunity to assess inter-annual variability, and the consistency of the results presented here in additional years. However, the number of sites do not seem to affect our results, as many previous studies have looked at the peak concentrations and the long-range transport for this region and have shown similar results (Field et al., 2016; Betha, Behera and Balasubramanian, 2014).

For uncertainties and error in HYSPLIT trajectory calculations normal to the direction of flow are 10-30% of the distance travelled after 24 h (Draxler and Hess, 1998). A trajectory is not representative of the path of an air parcel within the planetary boundary layer because the parcel quickly loses its identity through turbulent mixing processes (Stohl, 1998). However, the HYSPLIT model is adequate to classify regional-scale air mass motions in which local scale winds are embedded, which is consistent with their application in this study (Dotse et al., 2016). In applying the back trajectories in this study to assess the pathway taken by air masses prior to their arrival at measurements sites, the proportion of time spent over different countries (and the ocean) was calculated to provide a summary of the where the air mass travelled. This has been used to assess associations between time spent by air masses over different countries, and changes in hourly $PM_{10}$ concentrations. It is not possible to state definitively, based on this analysis, the contribution, e.g. of biomass burning in Myanmar vs Thailand to hourly $PM_{10}$ sites in Northern Thailand. This would require additional atmospheric chemistry transport modelling to investigate further. This study shows that measured hourly $PM_{10}$ concentrations were elevated when air masses traversed both Myanmar and northern Thailand during specific periods when previous studies have shown biomass burning to take place in both regions.

As summarised in Chapter 2, the measurement uncertainty of each hourly $PM_{10}$ concentration is $\pm 1$ μg $m^{-3}$. Based on the annual average $PM_{10}$ concentrations measured at each site, which varied from ~20 μg $m^{-3}$ in southern Thailand, to over 60 μg $m^{-3}$ in northern Thailand, the percentage uncertainty in each of these annual average $PM_{10}$

values ranges from ±5% for the lower value, to ±2% for the higher value. A key part of this study was the assignment of hourly $PM_{10}$ concentrations to 1 μg $m^{-3}$ bins, from which different statistics (e.g. % contribution to annual $PM_{10}$, % occurring in different months and hours of the day) were calculated. The measurement uncertainty indicates that some hourly $PM_{10}$ concentrations may have been assigned to a bin higher or lower than the actual $PM_{10}$ concentration for that hour, but, assuming that the measurement uncertainty is randomly distributed, this would not be expected to lead to a systematic error in the chemical climatology statistics calculated at each site. The limit of detection of the instrument could potentially result in a systematic error in the statistics calculated at low concentrations, but in practise the effect of the limit of detection was negligible in the analysis at all sites across northern and southern Thailand. Across all sites in northern Thailand between 2011 and 2015, there were a small number, on averages, only 2.1% of hours during which hourly $PM_{10}$ concentrations were below the limit of detection (< 4.8 μg $m^{-3}$ for a 1-hour measurement cycle).

## 3.5. Conclusion

The above results refer to the fact that particulate matter is the most influential air pollutant emitted from biomass burning in agricultural activities and forest fires, and it has a significant effect on air quality in Thailand, especially in the case of forest fires.

Measurements from the Thailand air pollution monitoring network were used to investigate the monthly, hour of day and country contributions to annual average $PM_{10}$ concentrations at different locations across Thailand. On average between 2011 and 2015, annual $PM_{10}$ concentrations were highest at sites in Northern and central Thailand, and lowest in Southern Thailand. This analysis also showed that in 2011, a >75% reduction in the extent of biomass burning in Northern Thailand and Myanmar resulted in a substantial reduction not only in the magnitude and frequency of peak $PM_{10}$ concentrations, but also in annual average $PM_{10}$ concentrations at sites across Northern Thailand. This reduction in emissions from biomass burning was sufficient to lead to no sites in northern Thailand exceeding the Thai national standard for annual $PM_{10}$ in 2011, in contrast to the widespread exceedance of the annual $PM_{10}$ standard in every other year considered in this analysis (2012-2015). The influence of long-range transport of smoke particles from other countries is clearly demonstrated in Southern Thailand. Air masses

also spend a substantial amount of time over the sea prior to their arrival at the monitoring sites but these areas still experiences haze episodes.

This study informs mitigation scenarios and action plans for reducing annual average $PM_{10}$ concentrations, and ensuring compliance with Thailand air quality standards. Specifically, to achieve this standard, minimisation of emissions from open burning areas in Northern Thailand during summer season (February-May), especially in March should be focussed on. Hence, reducing emission from biomass burning and forest fires can reduce annual $PM_{10}$ concentrations in Northern and Southern Thailand, which comply with annual $PM_{10}$ standards. Emissions reductions from biomass burning requires action on national and international scales, in both Thailand and neighbouring countries such as Myanmar, Indonesia, Malaysia and etc.

Finally, this study has shown that the 'chemical climatology' framework approach to analysing air pollution monitoring data can be used in a country like Thailand to derive policy-relevant conclusions on the link between air pollution impact metrics, and their causal drivers.

# Chapter 4: Assessment of conditions producing annual average $PM_{10}$ concentrations at general and roadside sites in Bangkok and central Thailand

## 4.1 Introduction

In Bangkok (a mega city) and central Thailand, air pollution from particulate matter in some areas still exceed the Thailand's national ambient air quality annual average standard. This chapter applies the same methodology applied in Chapter 3 to assess the contribution of biomass burning in northern and southern Thailand, to assess the more varied condition producing exceedance of the Thai national standard for annual average $PM_{10}$ in Bangkok and across central Thailand. The 'chemical climatology' analysis in Bangkok and central Thailand has been developed separately from the analysis in northern and southern Thailand due to the different and distinct characteristics of this region of Thailand, which are likely to result in different conditions driving exceedance of Thailand's annual $PM_{10}$ standard. Specifically, Bangkok is the only megacity in Thailand with a population of 5.8 million (within the main city itself). The next largest city in Thailand has a population of 270,000. Secondly, central Thailand contains much of Thailand's heavy industry, including cement manufacture in addition to other industrial processes. Finally, the air quality monitoring networks in Bangkok and central Thailand contain not only general sites but also roadside sites. This allows for the assessment of differences in the conditions producing annual $PM_{10}$ concentrations between different types of sites, which was not possible in other regions of Thailand.

The monitoring data from 34 monitoring sites, located across 8 provinces, for 2011 and 2015 were analysed. The variation in hourly $PM_{10}$ concentrations is combined with analysis of air mass back trajectories and meteorological measurements (temperature, wind speed, wind direction), to understand the contribution of different hourly $PM_{10}$ concentrations occurring during different months, hours of the day, geographic source regions and meteorological conditions to annual $PM_{10}$ concentrations at these sites. The analysis shows

how this approach can be used to explore the influence of local emissions (e.g. transportation, industrial productions) on annual average $PM_{10}$ concentration and the difference in air pollution conditions between general and roadside sites in Bangkok and central Thailand.

The aim of this analysis of variation of hourly $PM_{10}$ concentrations, and their effect on annual average $PM_{10}$ concentrations, is to explore the relative contribution of local emission sources and long-range transport to annual $PM_{10}$ at different sites, and to compare conclusions from analysis of sites in Bangkok with data obtained from other cities in Thailand.

# 4.2 Methods

A detailed explanation of the analysis of monitoring data used in this Chapter is given in Chapter 2. Basically, in the 'chemical climatology' framework was used to quantify the impact, state, and drivers producing annual average $PM_{10}$ concentrations at sites in Bangkok and central Thailand. Specifically, this involved calculating the contribution of hourly $PM_{10}$ concentrations in 1 $\mu g\ m^{-3}$ bins to the annual average $PM_{10}$ concentration at the site. Then, the percent of hourly $PM_{10}$ concentrations in each 1 $\mu g\ m^{-3}$ bins occurring in each month of the year and hour of the day were calculated. Finally, the proportion of time 4-day air mass back trajectories spent over Thailand, the ocean and neighbouring countries prior to arrival at the site was calculated for hourly $PM_{10}$ concentrations in each 1 $\mu g\ m^{-3}$ bin. These statistics were calculated for 34 sites across central Thailand (7 roadside sites and 11 general sites in Bangkok, and 16 general sites in the rest of central Thailand) for selected sites which had sufficient data capture above 75% of hourly observations across the year, for each month, and for each hour of the day between 2011 and 2015. Twenty four sites and 39 years were selected from 8 provinces (4 roadside sites and 7 general sites in Bangkok, and 13 general sites in the rest of central Thailand). For calculating annual average $PM_{10}$ concentrations between 2011 and 2015, there were only 7 general sites and 3 roadside sites in Bangkok and 13 general sites in central Thailand that met the data capture criteria in at least 3 of the 5 years as shown in Appendix, Table S11.

To present results in a concise way, example sites were selected for general sites in Bangkok, roadside sites in Bangkok, and general sites in central Thailand. In Bangkok, sites 6 and 9 (general site), sites 15 and 16 (roadside site) were selected, in central

Thailand, sites 49 and 24 (general site) were selected. These sites had the most years with sufficient data capture to assess the conditions producing annual $PM_{10}$ concentrations. Other sites of the same classification were then compared to these example sites, and finally, similarities and differences between roadside and general sites in Bangkok, general sites between Bangkok and central Thailand, and the rest of central Thailand were analysed.

In Bangkok, the classification of sites was divided into two types, general sites that are located in residential areas and roadside sites that are located next to roads as shown in red (general site) and green (roadside site) colour in Figure 4.1 (a). However, in central Thailand outside of Bangkok, there were only general monitoring sites and no roadside sites as shown in Figure 4.1 (b). Figures 4.1 (c) and (d) show the surrounded areas of Bangkok general and roadside sites.


**Figure 4.1:** Map of monitoring site locations and classification in (a) Bangkok (b) across Thailand (c) Bangkok general site and (d) Bangkok roadside site

## 4.3 Results

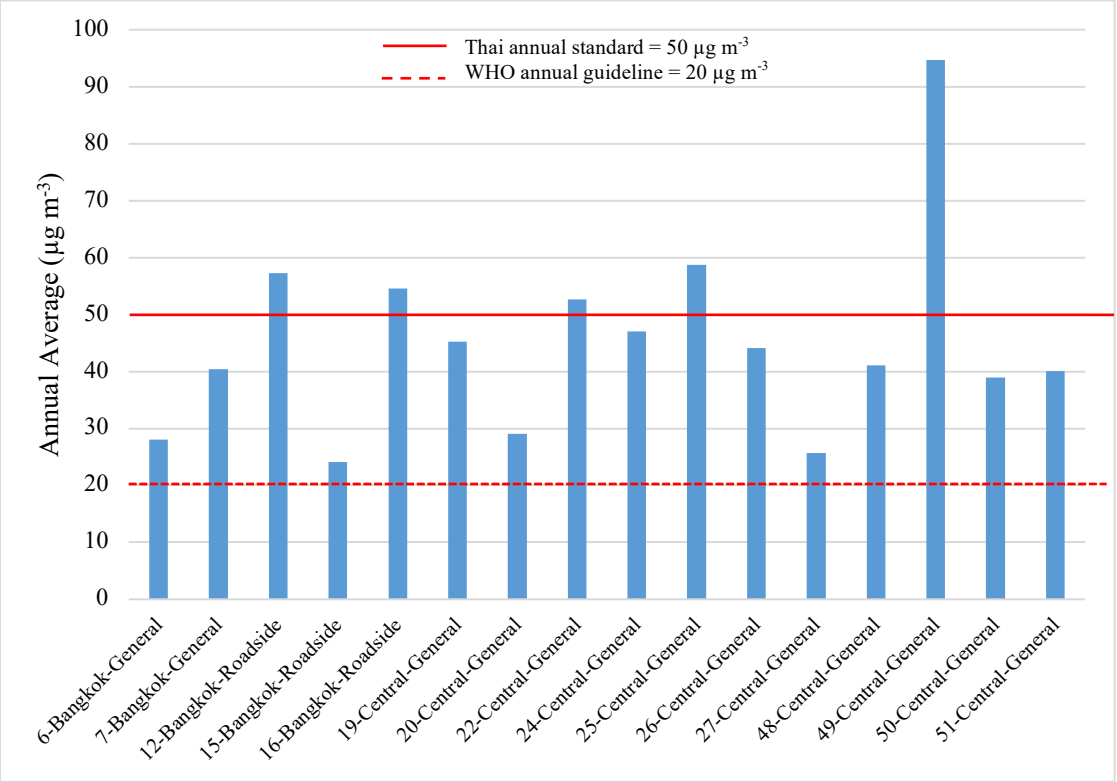
The following sections describe the contributions of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ concentrations at sites across Bangkok and central Thailand. Firstly, spatial variation in the annual average $PM_{10}$ concentration is summarised in Section 4.3.1 for sites across Bangkok and central Thailand because this is the key impact/regulatory metric related to human health effects, and the Thai $PM_{10}$ standard for protection of human health. Secondly, the conditions producing annual average $PM_{10}$ concentrations are summarised in Section 4.3.2. Assessment of the contributions of hourly $PM_{10}$ concentrations to the annual $PM_{10}$ concentrations are then presented first for those sites with the highest annual $PM_{10}$ concentrations (Section 4.3.2.1), followed by sites with more moderate values (Section 4.3.2.2), followed by those sites with the lowest annual $PM_{10}$ concentrations (Section 4.3.2.3).

### 4.3.1 Annual average $PM_{10}$ concentrations in Bangkok and central Thailand

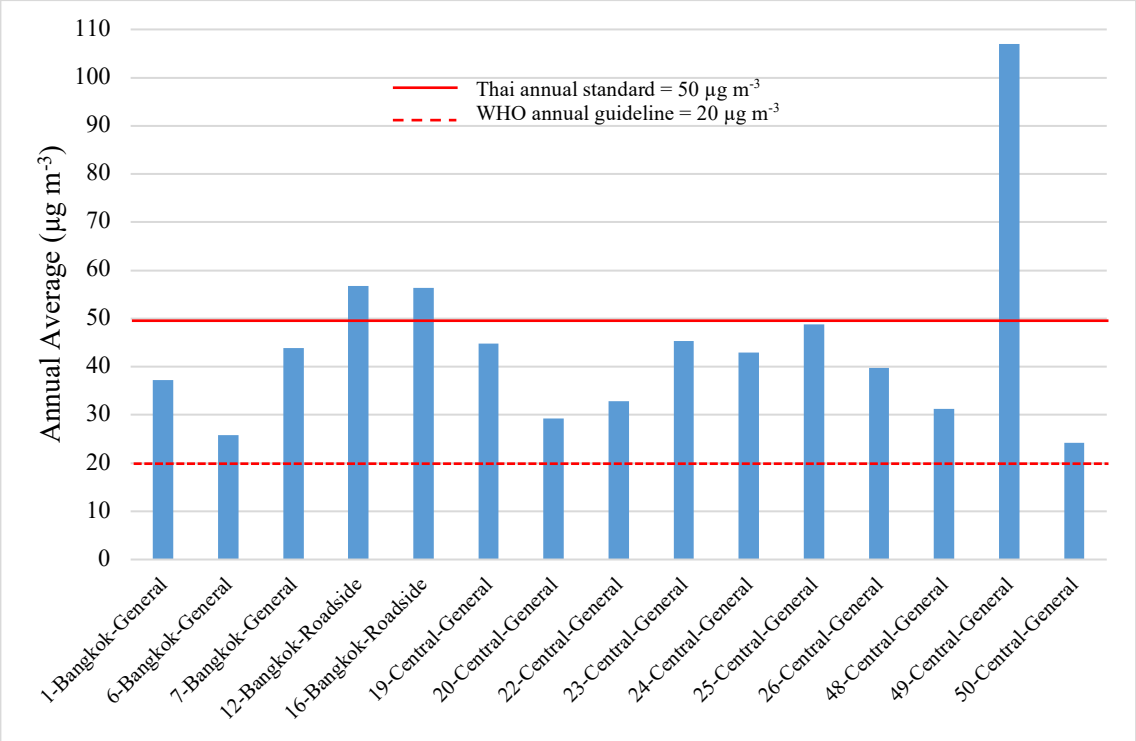
The annual average $PM_{10}$ concentrations between 2011 and 2015 in Bangkok and central Thailand were analysed and compared with the annual average $PM_{10}$ standard value of 50 $\mu g\ m^{-3}$. The results show that the annual average $PM_{10}$ concentrations for individual years at Bangkok and central Thailand between 2011 and 2015 were over the standard at 5, 3, 8, 9 and 3 sites in 2011, 2012, 2013, 2014 and 2015, respectively, as shown in Figure 4.2 (a-e). The annual average $PM_{10}$ concentrations for 2011 to 2015 in Bangkok were below the standard at 7 general and 1 roadside sites, and only 2 sites were over the standard at roadside sites but no general sites, as shown in Figures 4.3 and 4.4. Moreover, in central Thailand, there were 10 sites below and 3 sites over the standard, as shown in Figures 4.3 and 4.4. Figures 4.3 and 4.4 show the variation in annual average $PM_{10}$ concentrations at i) general sites in Bangkok, ii) roadside sites in Bangkok, and iii) general sites in the rest of central Thailand. The aim of these groupings is to compare the similarities and differences in annual average $PM_{10}$ concentrations, and the conditions producing them, between sites within and outside Bangkok in central Thailand, and between general and roadside sites in Bangkok, where the proximity of different source sectors may alter the pattern of $PM_{10}$ variation. At roadside sites in Bangkok, there was a much greater range of variation in annual average $PM_{10}$ concentrations compared with Bangkok and central general sites. Comparing general sites, in central Thailand, the annual average $PM_{10}$

concentrations were generally higher than general sites in Bangkok. The aim in assessing the variation in hourly $PM_{10}$ concentrations producing the annual average concentrations is to identify the reasons for these differences. Specifically, the aim is to identify what variation in hourly $PM_{10}$ concentration results in i) the higher annual $PM_{10}$ concentrations at central general sites outside of Bangkok, compared to in Bangkok, and ii) the substantially larger variation in annual $PM_{10}$ concentration across roadside sites.

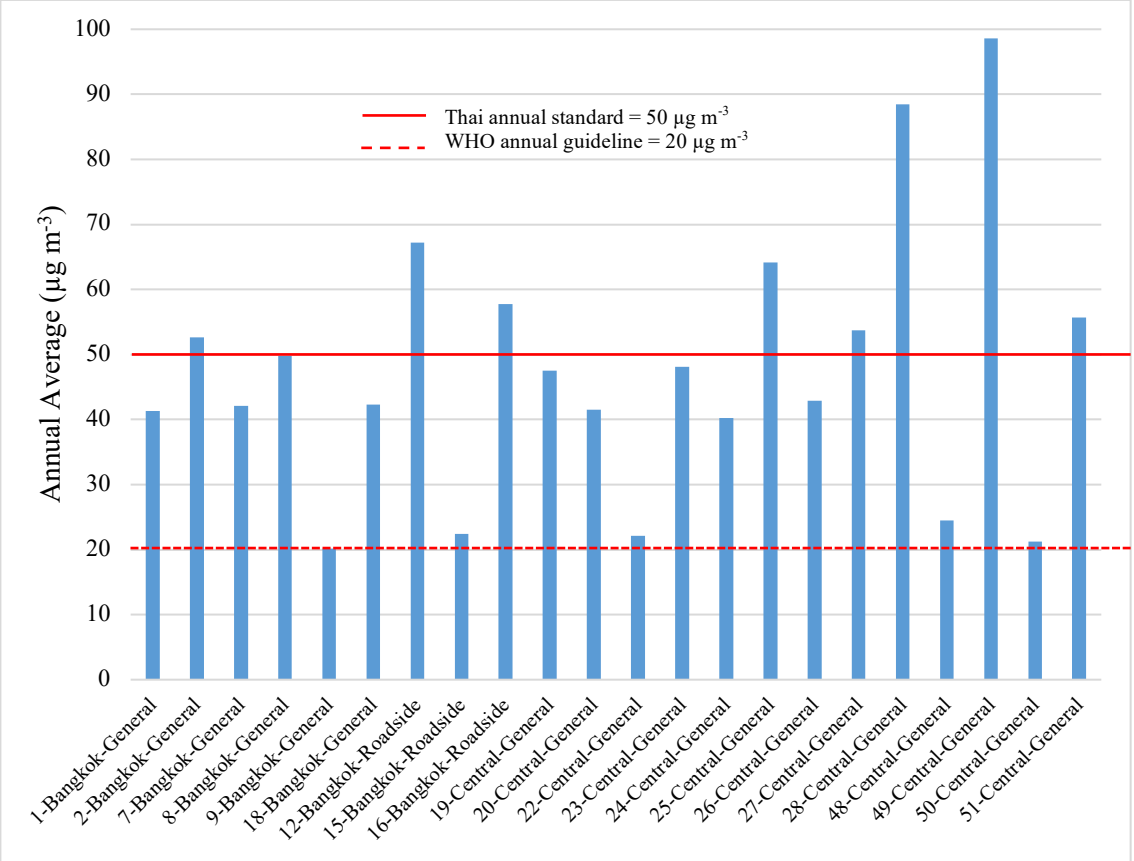
**(a) Annual Average $PM_{10}$ Concentration 2011**



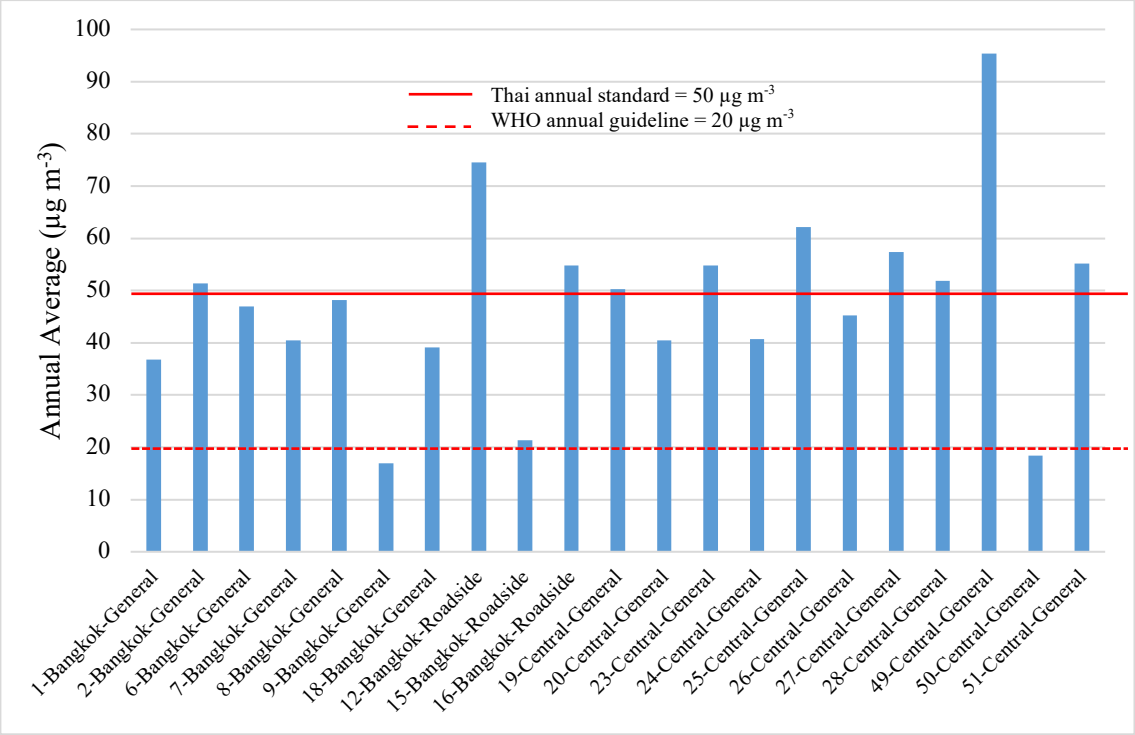
**(b) Annual Average $PM_{10}$ Concentration 2012**




**(c) Annual Average $PM_{10}$ Concentration 2013**



**(d) Annual Average $PM_{10}$ Concentration 2014**




**(e) Annual Average $PM_{10}$ Concentration 2015**

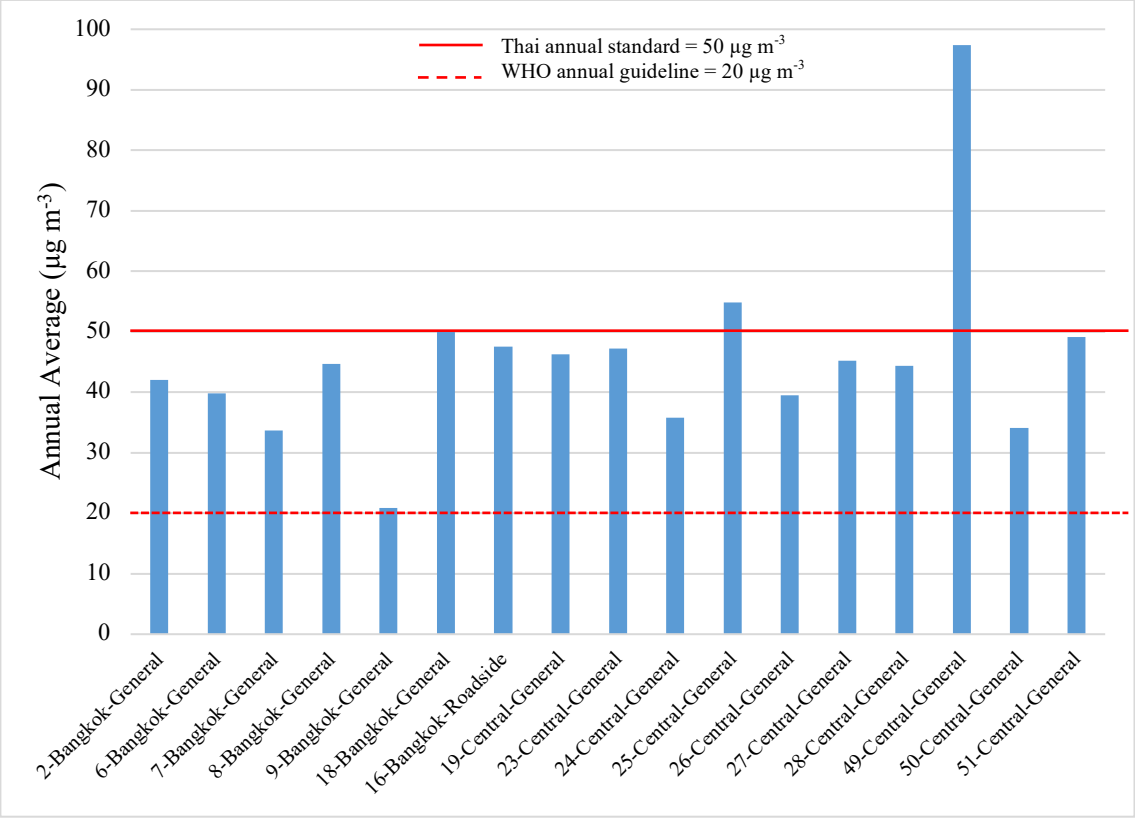



**Figure 4.2:** The annual average $PM_{10}$ concentrations for individual years at Bangkok and central Thailand for 2011 (a), 2012 (b), 2013 (c), 2014 (d) and 2015 (e).

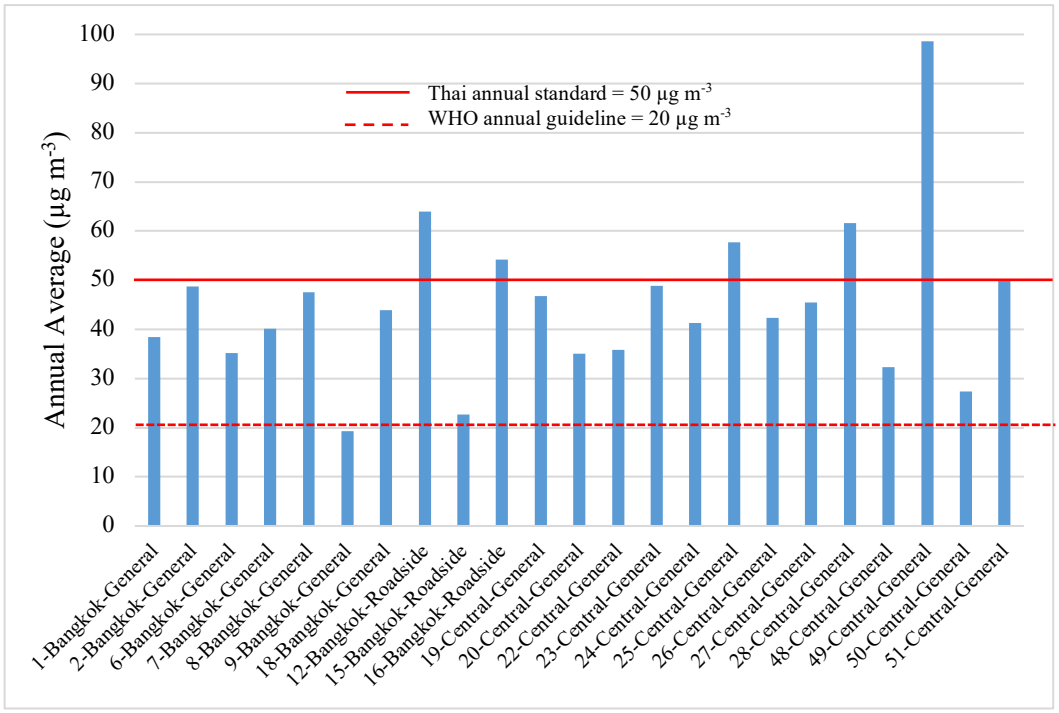



**Figure 4.3:** The comparison of annual average $PM_{10}$ concentrations across Thailand averaged for 2011 to 2015

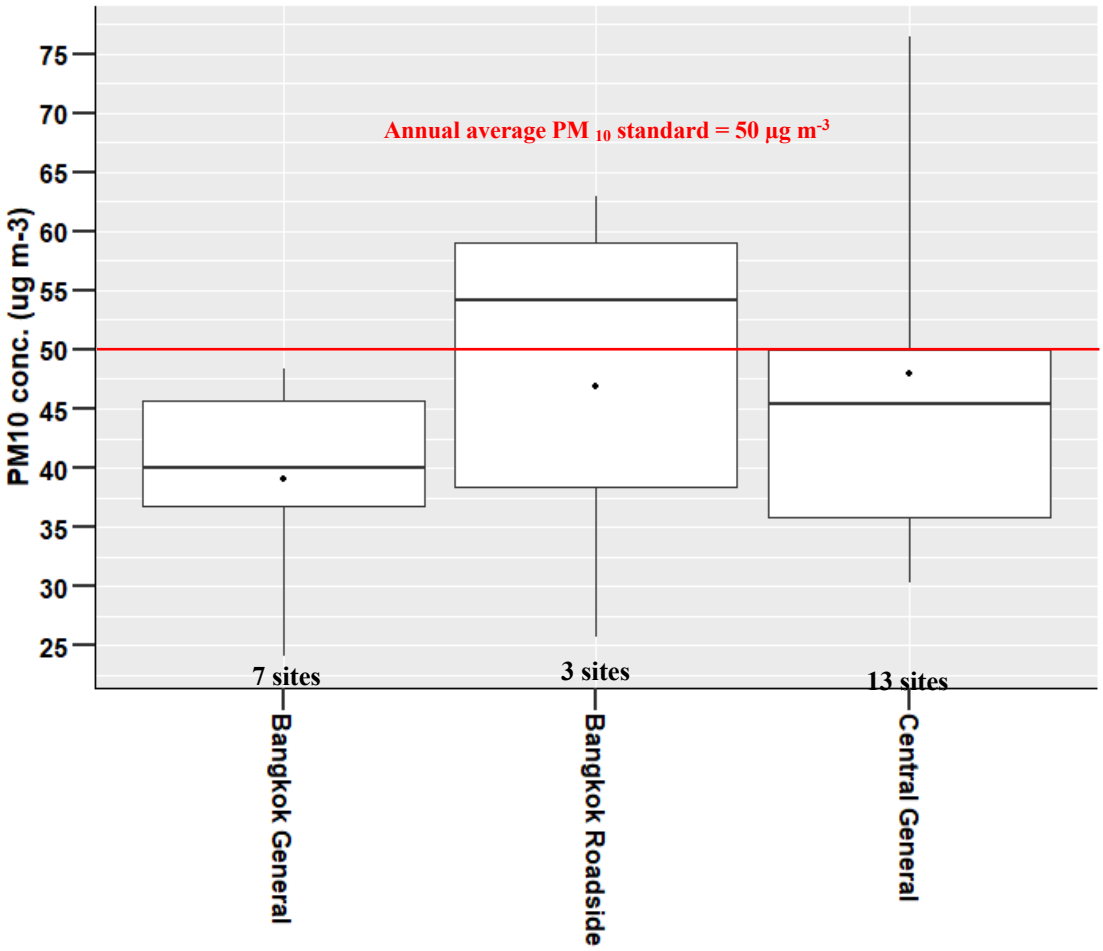
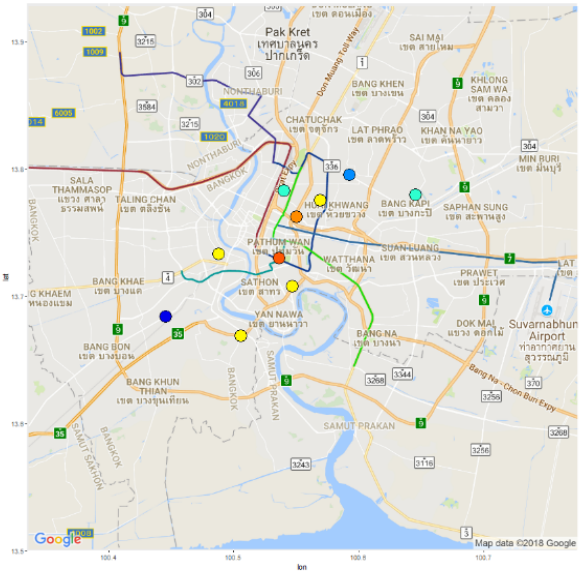


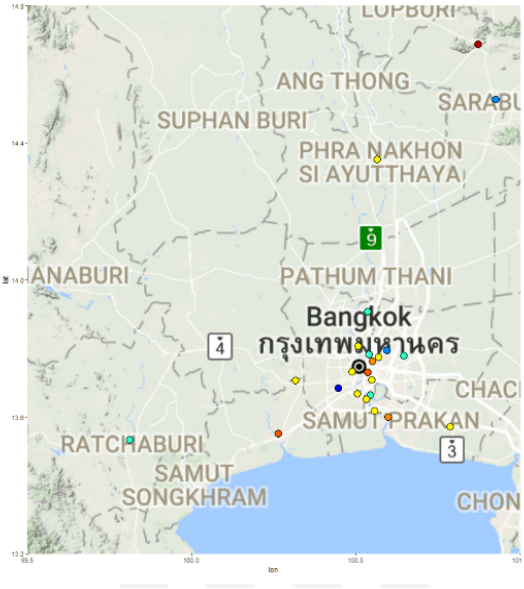

**Figure 4.4:** Box and whisker plots of the annual average $PM_{10}$ concentrations at general and roadside sites in Bangkok and central Thailand averaged for 2011 to 2015. The bottom of the box is 25$^{th}$ percentile, the top of the box is 75$^{th}$ percentile, the whiskers show the 5$^{th}$ and 95$^{th}$ percentile, the line is the median, the dot is the mean across all sites in each region and the red line is the annual average $PM_{10}$ standard

The variation in the 2011-2015 annual average $PM_{10}$ concentrations in Bangkok and central Thailand are shown in Figure 4.5 (a and b). There were two Bangkok roadside sites, and 3 central general sites exceeded the Thailand $PM_{10}$ standard of 50 µg m$^{-3}$. The largest annual $PM_{10}$ concentration that exceeded the standard in Bangkok was 64 µg m$^{-3}$ at a roadside site (site 12) and the lowest was 19.3 µg m$^{-3}$ at a general site (site 9). By contrast, in central Thailand, the highest value was 98.6 µg m$^{-3}$ at Saraburi site (site 49, general) and the lowest was 27.4 µg m$^{-3}$ at a different site in Saraburi province (site 50, general) as well.

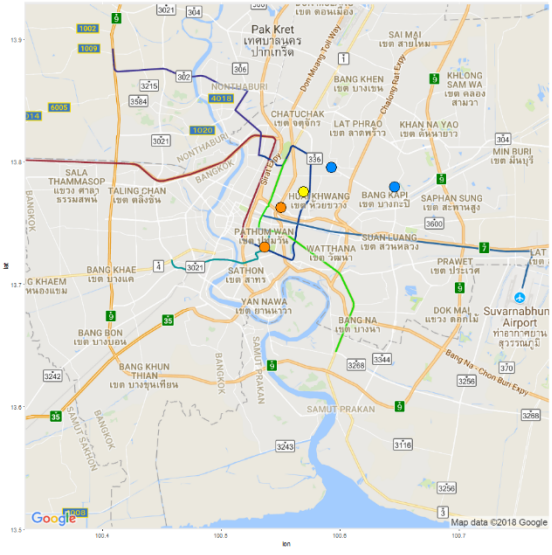
(a) Bangkok: 2011 - 2015



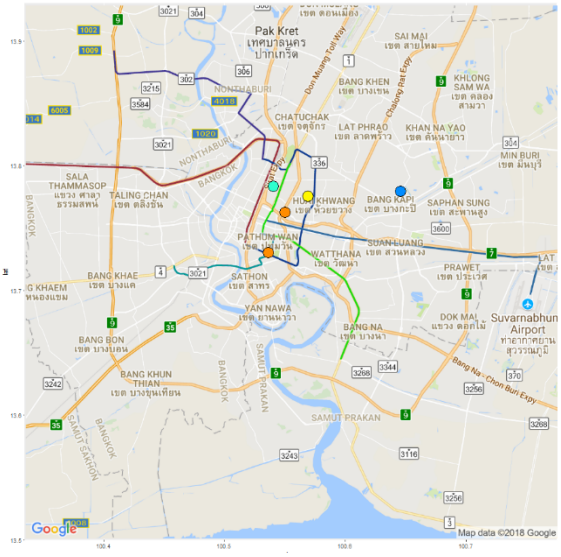

(b) Central: 2011 - 2015




(c) Bangkok: 2011



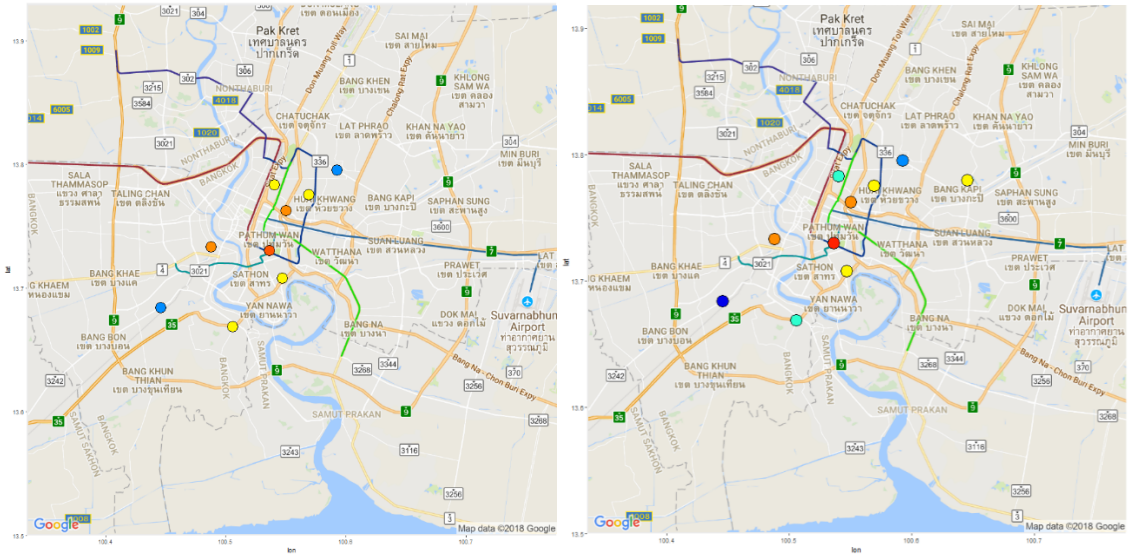

(d) Bangkok: 2012




$PM_{10}$ ($\mu g\ m^{-3}$)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 10-20 | | 30-40 | | 50-60 | | 90-100 |
| | 20-30 | | 40-50 | | 60-70 | | |

(e) Bangkok: 2013 (f) Bangkok: 2014




(g) Bangkok: 2015

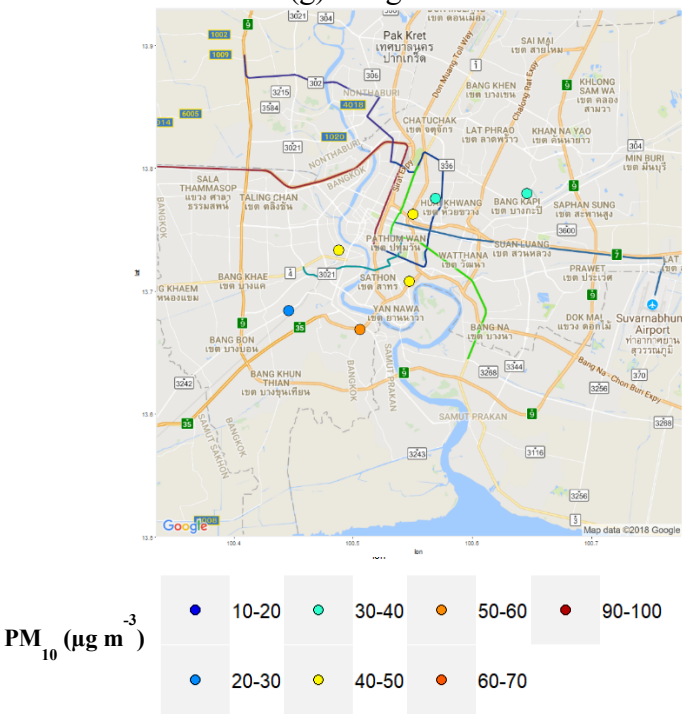



**Figure 4.5:** Annual average $PM_{10}$ concentrations for the monitoring sites averaged between 2011 and 2015 in (a) Bangkok (b) across central Thailand (including Bangkok) and for individual years in Bangkok (c) 2011 (d) 2012 (e) 2013 (f) 2014 and (g) 2015

The annual average $PM_{10}$ concentrations in Bangkok between 2011 and 2015 showed a much wider range compared to other regions of Thailand, varying from 10 up to 70 µg $m^{-3}$ (Figure 4.5a). This variation was mainly due to large variation across the roadside sites (Figure 4.4). Roadside monitoring sites are only located in Bangkok, and not in other Thai cities. Monitoring of roadside $PM_{10}$ (and $PM_{2.5}$) concentrations in other cities in Thailand would allow assessment of whether similar large variation in $PM_{10}$ concentrations occur at roadside locations across Thailand, and whether there is greater variation in roadside $PM_{10}$ compared to general site $PM_{10}$ in other Thai cities.

The majority of sites in Bangkok and central Thailand had annual average $PM_{10}$ concentrations between 2011 and 2015, that ranged from 10 up to 80 µg $m^{-3}$ (Figure 4.5). The annual average $PM_{10}$ concentrations at roadside sites exceeded the standard for site 12 and site 16 in 2011, 2012, 2013, and 2014. Moreover, there were two general sites exceeding the standard at site 2 in 2013 and 2014 and at site 18 in 2015. However, in central Thailand, the patterns were different in annual average $PM_{10}$ concentrations. A general site in Saraburi province (site 49) was over the standard for every year during 2011 to 2015 (see Appendix, Figure S1). Across central Thailand, 2014 showed the highest number of sites over the standard (10 sites) (see Appendix, Figure S1). The patterns for the variation of annual average $PM_{10}$ concentrations across the different years between 2011 and 2015 in central Thailand varied from 10 up to over 100 µg $m^{-3}$ (see Appendix, Figure S1).

In summary, the highest annual $PM_{10}$ concentration in central Thailand occurred at general sites outside Bangkok, but there was large variation among these sites. The majority of sites in central Thailand exceeding the Thai annual $PM_{10}$ standard were roadside sites in Bangkok, while the lowest annual average $PM_{10}$ concentrations occurred at Bangkok general sites, which also had the lowest variability between sites.

### 4.3.2 Conditions producing annual average $PM_{10}$ concentrations

Analysis of conditions producing annual average $PM_{10}$ concentrations are separated into three sections in i) high concentrations of annual average $PM_{10}$ (Section 4.3.2.1), ii) moderate concentrations of annual average $PM_{10}$ (Section 4.3.2.2), and iii) low concentrations of annual average $PM_{10}$ (Section 4.3.2.3). The aim of this section is to investigate the reasons for differences and similarities in annual average $PM_{10}$ concentrations between sites. Specifically, this includes understanding the reasons for the larger variability in annual $PM_{10}$ concentrations at roadside sites in Bangkok, compared to general sites, and the reason why annual $PM_{10}$ concentrations at general sites in central Thailand are generally higher than general sites in Bangkok.

A summary of hourly $PM_{10}$ concentrations contributions to the annual average across different central Thailand and Bangkok sites in 2015 is shown in Figure 4.6 and other years in Figure S2 (see Appendix). This plot shows the percentage contribution of hourly $PM_{10}$ concentrations to the annual average from low concentrations (site 14, roadside site in Bangkok) which had a low frequency of the highest concentrations to high concentrations (site 49, general site in central Thailand) which had a high frequency of the highest concentrations in a heavily industrialised area that contributed 60 to 70% of the annual average. This plot demonstrates that the reason for the large variation in annual average $PM_{10}$ concentrations across Bangkok and central Thailand is due to differences in the hourly $PM_{10}$ frequency distribution at different sites. At Site 49 in central Thailand, more than 60% of hourly $PM_{10}$ concentrations are above 100 $\mu g\ m^{-3}$, while these make up 20% or less at all other sites in this region.

Similar findings from previous studies in these areas associated with $PM_{10}$ have been reported at different monitoring sites in Bangkok and central Thailand. For example, Chuersuwan et al. (2008) studied on $PM_{10}$ concentration at four sites in Bangkok area which air quality was influenced by automobile emissions and biomass burning. This study found that the 24-hour averages of $PM_{10}$ concentrations were high at roadside sites contributed 33% from both automobile emissions and biomass burning. However, at two residential (general) sites, automobiles contributed 39 and 22% while biomass burning contributed 36 and 28%. In central Thailand, the PCD declared that Na Phra Lan subdistrict is a pollution control zone in Saraburi province (same area as site 49) (PCD, 2014). The 24 - hour average of $PM_{10}$ in this area frequency exceeded the standard,

especially during dry season (from October - March of each year) which mainly from cement productions, stone crushing and lime plants, quarries in the area and nearby, as well as transportation and logistics activities (PCD, 2018). Pimonsree, Wongwises and Pan-aram (2008) studied on dispersions of $PM_{10}$ during winter and rainy seasons in Saraburi. The result showed that the main sources of $PM_{10}$ came from mineral products industrial area (76% of $PM_{10}$ was emitted from resuspended road dust and crushed stone plants).The distributions of $PM_{10}$ concentrations during winter were influenced by the northeast monsoon (prevailing wind was northeasterly wind) and under the influence of the southwest monsoon in rainy season (prevailing winds were southwesterly and southerly winds) (Pimonsree *et al.*, 2009). Phetrawech and Thepanondh (2017) studied on evaluation of $PM_{10}$ emissions from a road network at the Na Phra Lan site in Saraburi province. The result showed that 71% contribution of the highest predicted $PM_{10}$ concentration came from mobile source emissions (re-suspended road dust).

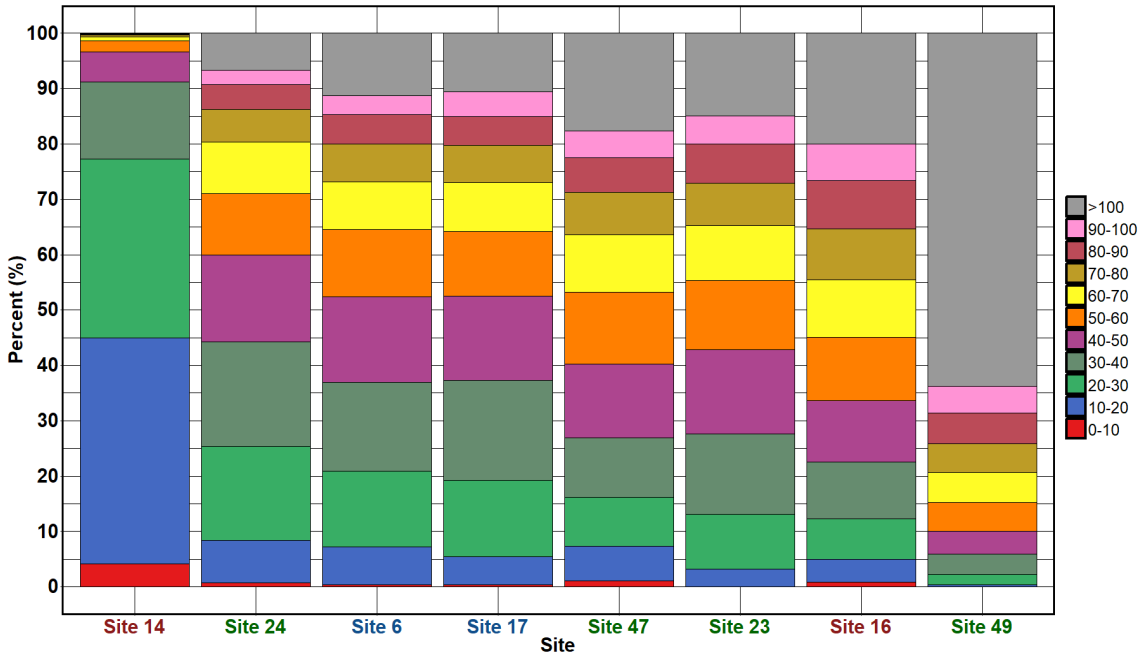



**Figure 4.6:** Summary of hourly $PM_{10}$ concentrations contribution to annual average across central Thailand and Bangkok sites in 2015

Figure 4.7 shows a summary of hourly $PM_{10}$ concentrations contribution to annual average from monthly, hourly and country contribution across central Thailand sites in 2015 (see Appendix, Figure S3 for 2011, 2012, 2013 and 2014). Each of the panels shows how hourly $PM_{10}$ concentrations between 0 to 10 and greater than 100 µg $m^{-3}$ occurred. The top plot shows the months when those hourly concentrations occurred in these sites. The lowest concentrations occurred during the rainy season across the majority of sites. The highest concentrations occurred during the dry season. However, high concentrations also occurred during the rainy season months. This suggesting that these sites still get the effect from the local emission sources contributing to higher $PM_{10}$ concentrations. The second plot shows the hourly contributions, with the highest concentrations occurring during the evening and some in the morning rush hour. The last plot shows a large proportion of time spent over Thailand for the highest concentrations. In the rainy season the air mass comes from the sea, in the dry season comes from neighbouring countries and over Thailand.

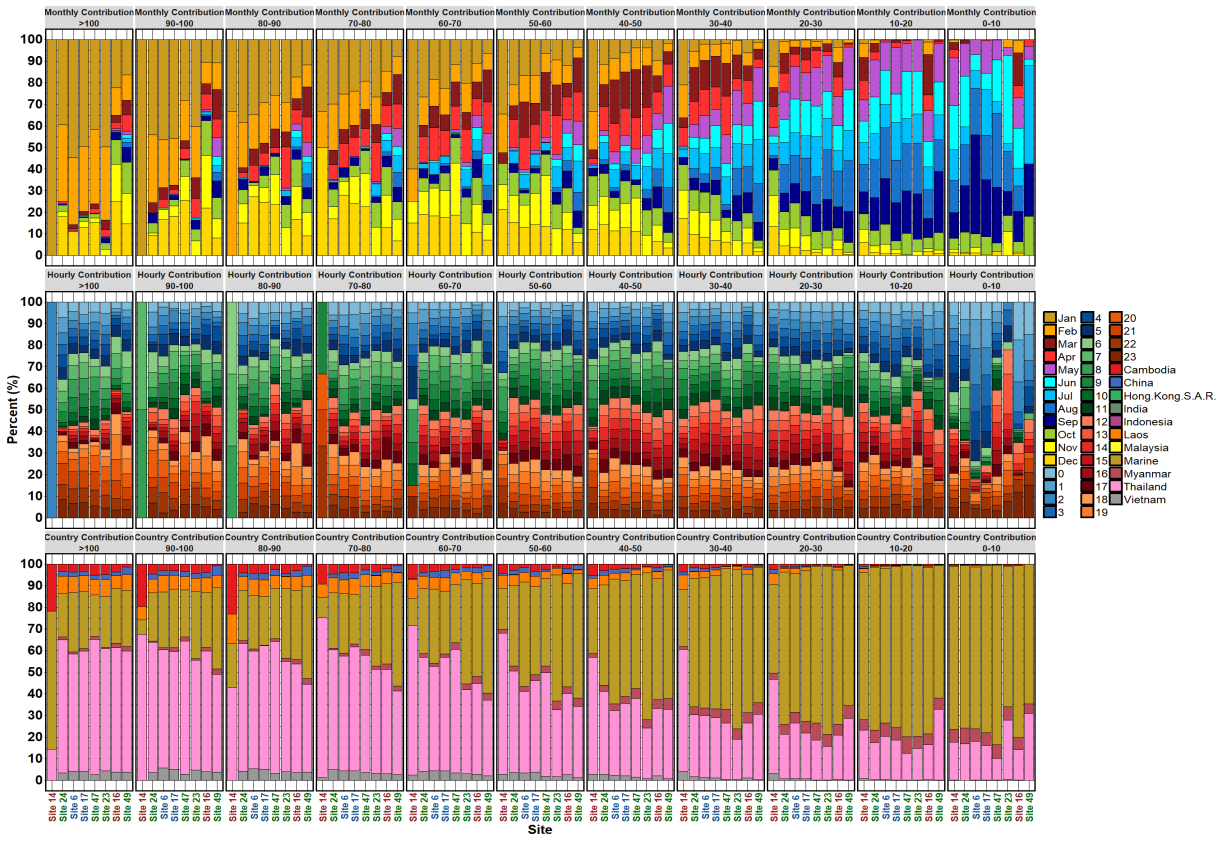



**Figure 4.7:** Summary of hourly $PM_{10}$ concentrations contribution to annual average from monthly, hourly and country contribution across central Thailand sites in 2015

### 4.3.2.1 High concentrations of annual average $PM_{10}$

The sites with highest annual average $PM_{10}$ concentrations (> 50 μg $m^{-3}$) between 2011 and 2015 in central Thailand and Bangkok were roadside sites in Bangkok, and general sites in central Thailand located in heavily industrialised areas. Analysis of the distributions of hourly concentrations contributing to annual $PM_{10}$ concentrations at these sites indicates that large local emission sources determine the elevated annual $PM_{10}$ concentrations. This is shown for two example sites (out of 5 sites above 50 μg $m^{-3}$, see Appendix, Table S12), one a roadside site in Bangkok (Site 16), and one a general site in central Thailand (Site 49), where 2011-2015 annual average $PM_{10}$ concentrations were 54.2 μg $m^{-3}$ and 98.6 μg $m^{-3}$, respectively, 9% and 13% above the average across all sites in Bangkok and central Thailand with sufficient data capture as shown in Table 4.1 and Table S12 (Appendix).

**Table 4.1:** Annual average $PM_{10}$ concentrations (μg $m^{-3}$) at monitoring sites across central Thailand that exceeded the Thai National standard for annual $PM_{10}$ concentrations between 2011 and 2015

| Site | Category | Province | Region | 2011 | 2012 | 2013 | 2014 | 2015 | 2011-2015 | Level |
|---|---|---|---|---|---|---|---|---|---|---|
| 12 | Roadside | Bangkok | Central | 57.3 | 56.8 | 67.2 | 74.5 | - | 64.0 | High |
| 16 | Roadside | Bangkok | Central | 54.6 | 56.4 | 57.8 | 54.8 | 47.6 | 54.2 | High |
| 25 | General | Samut Prakan | Central | 58.7 | 48.8 | 64.2 | 62.1 | 54.9 | 57.7 | High |
| 28 | General | Samut Sakhon | Central | - | - | 88.5 | 51.8 | 44.3 | 61.6 | High |
| 49 | General | Saraburi | Central | 94.7 | 107.0 | 98.6 | 95.4 | 97.3 | 98.6 | High |

The conditions producing annual average $PM_{10}$ concentrations at an example roadside site in Bangkok for the year 2015 are shown in Figures 4.8 and 4.9, Table 4.2 and Tables S13-S15 (See Appendix). This site, National Housing Authority Dindaeng site (site 16), had sufficient data capture in the largest number of years, and was therefore the primary site used to evaluate how variation in hourly $PM_{10}$ concentrations contributed to the annual average for roadside sites in Bangkok. At this site in 2015, the 'very high' hourly $PM_{10}$ concentrations above the $95^{th}$ percentile (110 μg $m^{-3}$) were as high as 250 μg $m^{-3}$ and contributed 12% to the $PM_{10}$ annual average (Figure 4.8a and Table 4.2). These very high $PM_{10}$ concentrations occurred mainly during winter season (mid-October to mid-February), in particular in January (27% of all very high concentrations), in December (23%) and February (16%), while the lowest hourly $PM_{10}$ concentrations occurred in June (Figure 4.8b). This reflects the higher $PM_{10}$ concentrations that occur during the dry season (winter (mid-October to mid-February) vs summer seasons (mid- February to mid-May)) compared to the rainy season (mid-May to mid-October).

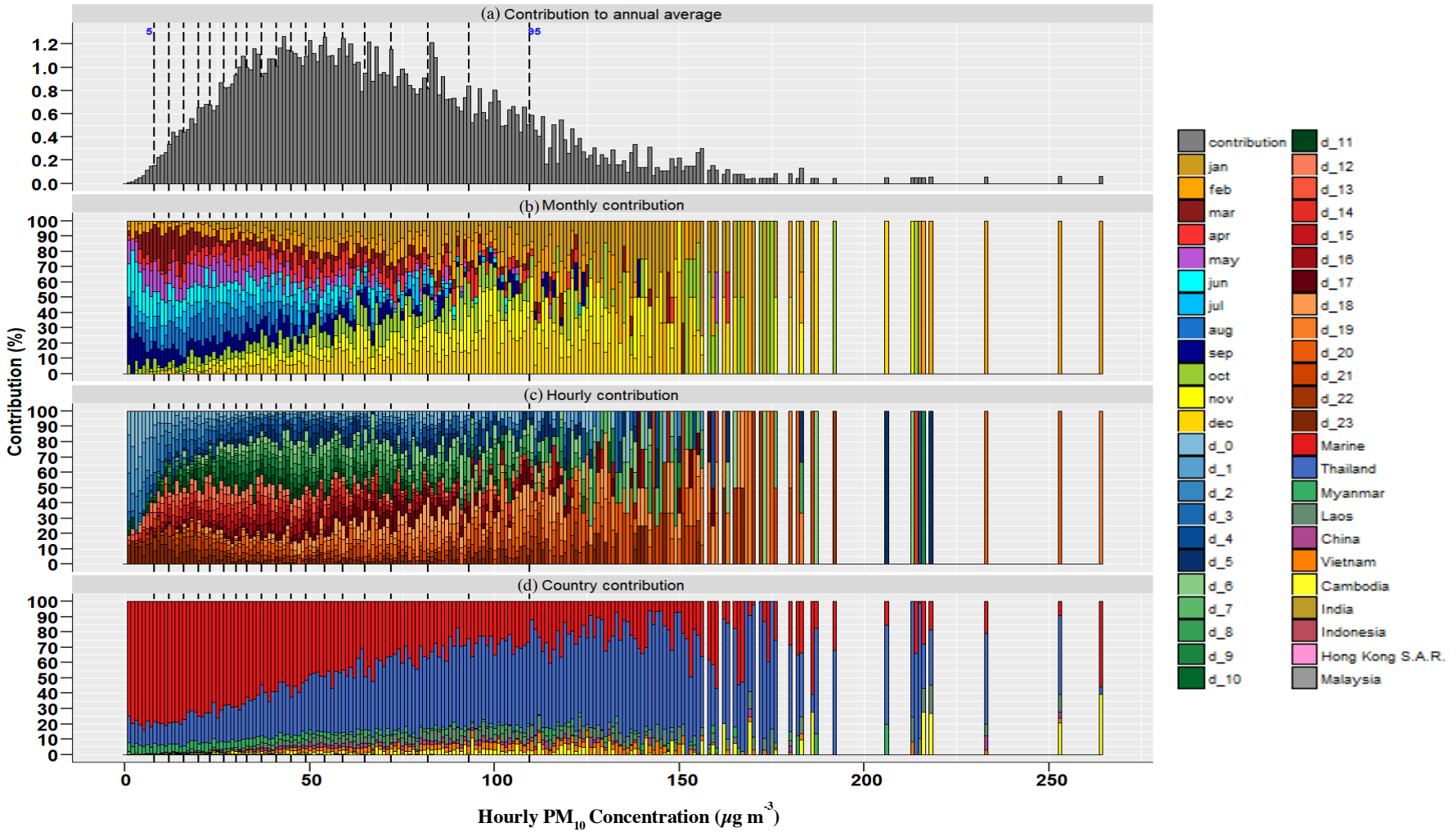
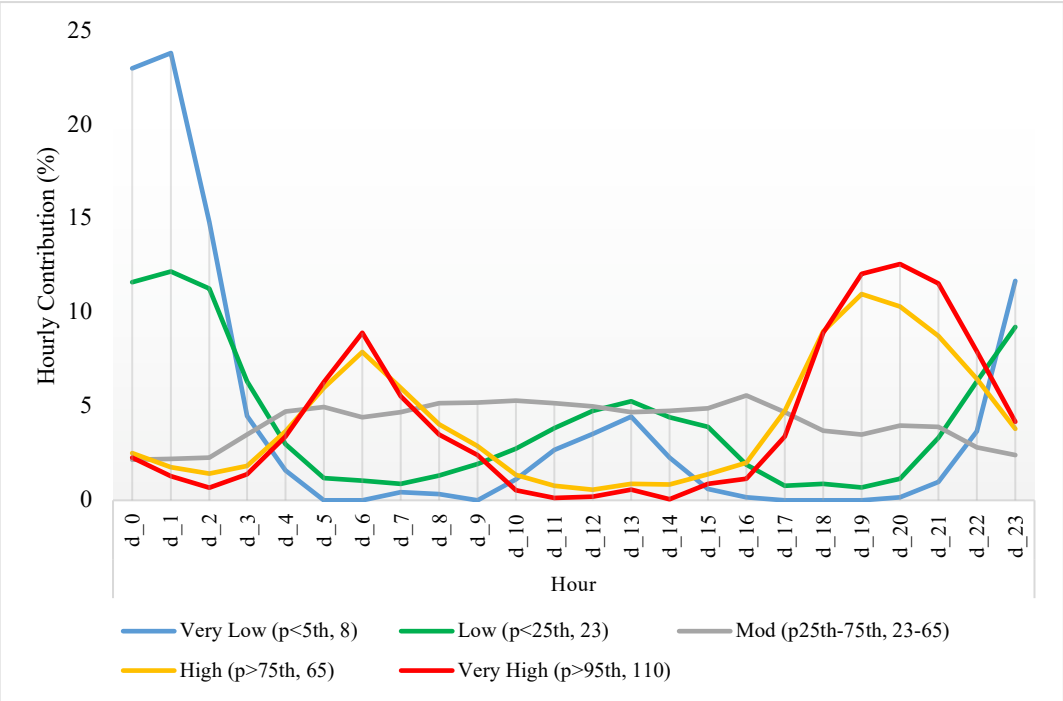



**Figure 4.8:** The different conditions producing annual average $PM_{10}$ concentrations at site 16, roadside sites in Bangkok, 2015

**Table 4.2:** Comparison of the main conditions producing annual average $PM_{10}$ concentrations at site 16, roadside sites in Bangkok

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly contribution (%) | | | | | | Country contribution (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Jun | Oct | Nov | Dec | Cambodia | Laos | Marine | Thailand | Vietnam |
| Bangkok (Site 16) | Roadside site | 2015 | Very Low | <5th Percentile | <8 | 0 | 1 | 7 | 23 | 5 | 0 | 1 | - | 0 | 80 | 14 | 0 |
| | | | Low | <25th Percentile | <23 | 6 | 1 | 6 | 15 | 5 | 1 | 1 | 0 | 0 | 78 | 16 | 0 |
| | | | Moderate | 25th-75th Percentile | 23-65 | 38 | 9 | 7 | 8 | 9 | 8 | 8 | 1 | 3 | 57 | 31 | 2 |
| | | | High | >75th Percentile | >65 | 43 | 22 | 14 | 1 | 15 | 14 | 21 | 4 | 6 | 26 | 57 | 3 |
| | | | Very High | >95th Percentile | >110 | 12 | 27 | 16 | - | 16 | 13 | 23 | 4 | 6 | 23 | 61 | 3 |
| | | 2013 | Very Low | <5th Percentile | <13 | 1 | 0 | 1 | 12 | 4 | 1 | 3 | 1 | 1 | 74 | 18 | 1 |
| | | | Low | <25th Percentile | <31 | 7 | 2 | 3 | 11 | 3 | 3 | 2 | 1 | 1 | 74 | 18 | 1 |
| | | | Moderate | 25th-75th Percentile | 31-78 | 39 | 8 | 6 | 9 | 9 | 11 | 6 | 1 | 3 | 56 | 32 | 3 |
| | | | High | >75th Percentile | >78 | 41 | 22 | 23 | 2 | 10 | 4 | 25 | 2 | 6 | 22 | 64 | 3 |
| | | | Very High | >95th Percentile | >120 | 12 | 25 | 31 | 1 | 7 | 1 | 26 | 2 | 6 | 18 | 69 | 3 |

(a) 2015




(b) 2013

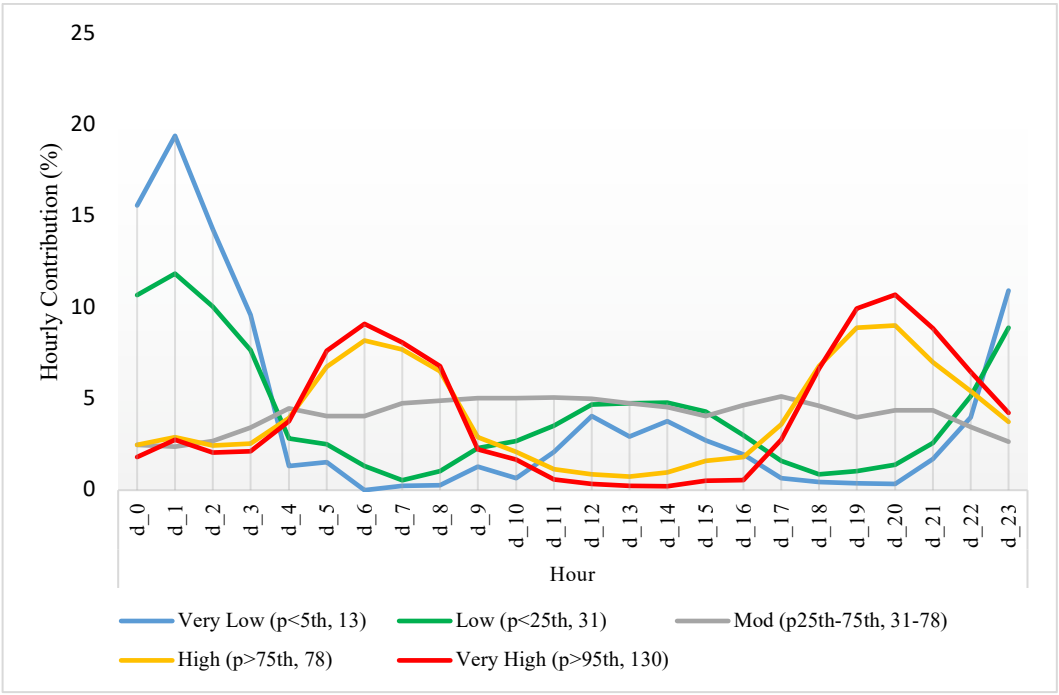
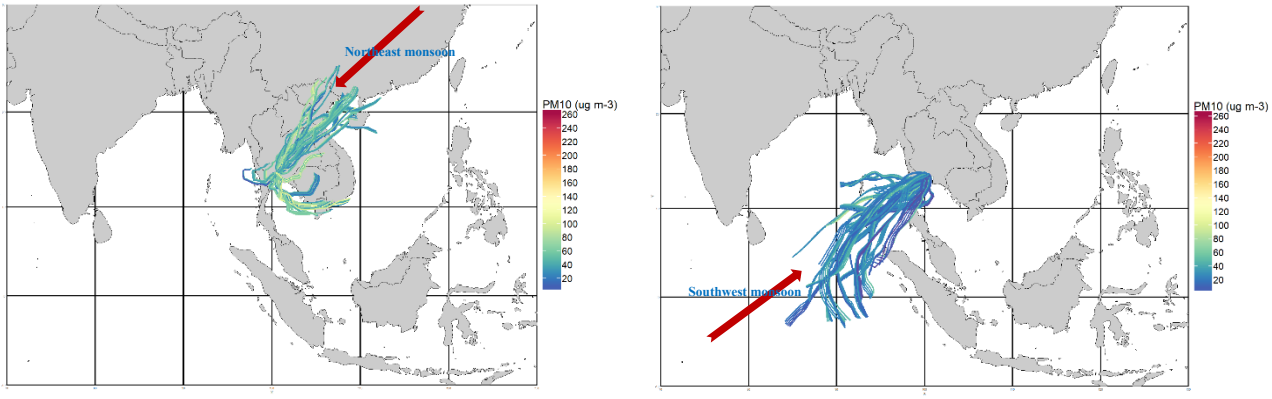



**Figure 4.9:** The percentage of hourly $PM_{10}$ concentrations in different ranges ('very high' $PM_{10}$ concentrations above the 95$^{th}$ percentile; 'high' above 75$^{th}$ percentile, 'moderate between 25 and 75$^{th}$ percentile, 'low' below the 25$^{th}$ percentile, and 'very low' below the 5$^{th}$ percentile) that occurred during different hours of the day at Site 16, a roadside site in Bangkok in (a) 2015 and (b) 2013

The influence of local emissions is reflected in the diurnal variation in hourly $PM_{10}$ concentrations at site 16. For example, Figure 4.9 shows the percentage of hourly $PM_{10}$ concentrations in different ranges, the 'very high' concentrations occurred most frequently during the morning and evening rush hour periods. The different lines in Figure 4.9 show the diurnal variation in different levels of concentrations at the same site but they do not show diurnal cycles at different sites. The red and yellow lines show the variation across the day in high concentrations at one site, and the other lines show the variation across the day in lower concentrations, at the same site. The diurnal variability of $PM_{10}$ levels in different years in 2013 (Figure 4.9a) and 2015 (Figure 4.9b) shows the similar trends. The morning rush hour is between 6:00 a.m. and 9:00 a.m. and the evening rush hour is between 4:00 p.m. and 7:00 p.m. (Ministry of Transport, 2015). In 2015, during the evening rush hour, 26% of the very high concentrations occurred (the red line, concentration above 110 $\mu g\ m^{-3}$), with 20% occurring during the morning rush hour. The lowest hourly $PM_{10}$ concentrations (the blue line, concentration below 8 $\mu g\ m^{-3}$) occurred during the night, and the moderate concentrations (the grey line, concentration between 23 -65 $\mu g\ m^{-3}$) occurred more evenly throughout the day (Figures 4.8c and 4.9a), and 2013 (Figure 4.9b) also shows the similar trends. This is consistent with this roadside site being closer to, and therefore hourly $PM_{10}$ concentrations being determined to a greater extent by, a large local road transport emission source.

The 4-day back trajectory air masses showed the largest differences between winter (northeast monsoon season) and rainy (southwest monsoon season) seasons. During winter season (mid-October to mid-February), the dominant trajectory pathway was northeast (Figure 4.10a), compared to southwest during rainy season (mid-May to mid-October) (Figure 4.10b). Hence the very high concentrations, occurring predominantly in winter, occurred during the arrival of air masses that spent a large portion of time over Thailand (61% on average), the ocean (23%), but also Cambodia (4%), Laos (6%) and Vietnam (3%) as shown in Figure 4.8d and Table 4.2. However, there is also variation in the proportion of very high hourly $PM_{10}$ concentrations that occur during different months in winter, without substantial differences in the air mass pathway traversed prior to arrival at the site. This suggests that regional transport of air pollution may make a smaller contribution to annual $PM_{10}$ concentrations at this site compared with local emission sources, especially when compared with the stronger association between air mass origin and hourly $PM_{10}$ concentration observed in other regions of Thailand (i.e. northern and southern Thailand), discussed in Chapter 3.




(a) January (b) June

**Figure 4.10:** Comparison the differences of 4-day backward air masses trajectory plots at site 16 in Bangkok 2015 between (a) January (winter) and (b) June (rainy) seasons. Each line represents the air mass back trajectory arriving at the site at 12 pm during each day in the month, and is coloured according to the hourly $PM_{10}$ concentration measured during its arrival.

Finally, analysis of the hourly $PM_{10}$ concentrations coinciding with different meteorological conditions also suggests that local emission sources dominate at roadside site 16. There was little association between hourly $PM_{10}$ concentrations and hourly temperature and wind direction. This indicates that temperature-sensitive chemical processing of pollutants in the atmosphere (e.g. gas-aerosol phase partitioning) that determine $PM_{10}$ concentrations may not have sufficient time to proceed between emission and arrival at the receptor site for site 16. However, in winter, there was a propensity for higher hourly $PM_{10}$ concentrations to occur when wind speed were relatively low (generally below 1 $ms^{-1}$), with lower concentrations occurring when wind speed was elevated. This indicates that dispersion of emissions from local traffic emissions may be an important meteorological parameter in determining hourly $PM_{10}$ concentrations.

Similar patterns were also seen for 2013 at site 16.

The second example site with the highest annual average $PM_{10}$ concentrations in central Thailand is site 49 at Na Phra Lan Subdistrict, Saraburi. This site is a critical air quality area which had the largest number of years with sufficient data capture, and had the largest annual $PM_{10}$ concentration in central Thailand, consistently exceeding the Thai national $PM_{10}$ standard. The statistics summarising the contributions of hourly $PM_{10}$ concentrations to the annual average $PM_{10}$ at this site, for 2015, are shown in Figure 4.11, Table 4.3 and Tables S13-S15 (See Appendix)**,** and also indicate that local emission sources play a major role in determining the elevated annual $PM_{10}$ concentration at this site.

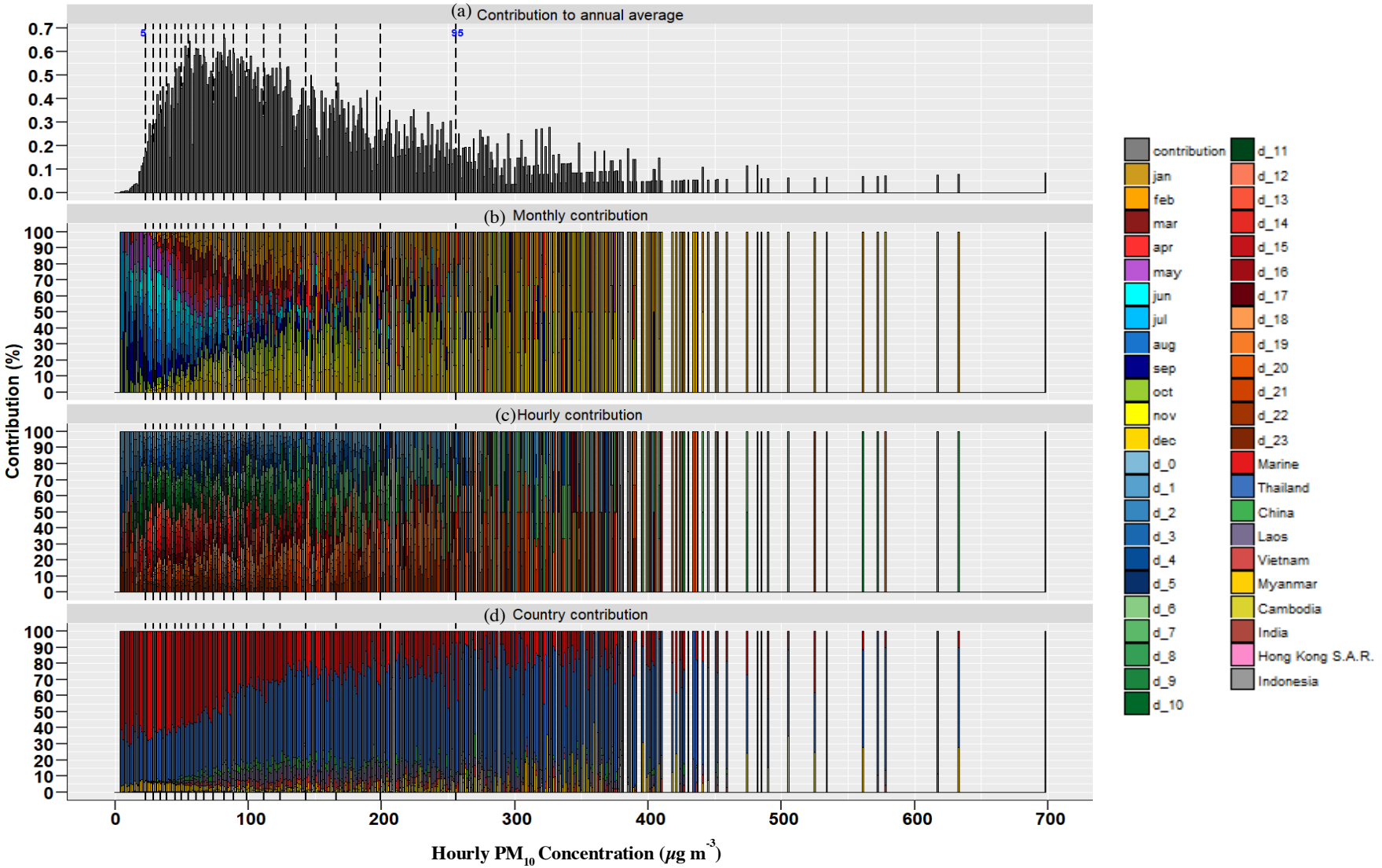



**Figure 4.11:** The different conditions producing annual average $PM_{10}$ concentrations at site 49, general site in Saraburi province in central Thailand, 2015

**Table 4.3:** Comparison of the main conditions producing annual average $PM_{10}$ concentrations at site 49 in Saraburi province

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | Country Contribution (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration (µg $m^{-3}$) | | Jan | Feb | Oct | Nov | Dec | Laos | Marine | Myanmar | Thailand | Vietnam |
| **Saraburi** | General site | 2015 | Very Low | <5th Percentile | <23 | 1 | - | 0 | 10 | 1 | 0 | 0 | 64 | 5 | 30 | 0 |
| | | | Low | <25th Percentile | <45 | 7 | 0 | 2 | 6 | 1 | 1 | 0 | 63 | 5 | 30 | 0 |
| | | | Moderate | 25th - 75th Percentile | 45-124 | 34 | 9 | 9 | 8 | 8 | 8 | 5 | 44 | 3 | 41 | 3 |
| | | | High | >75th Percentile | >124 | 45 | 26 | 11 | 12 | 15 | 19 | 7 | 20 | 3 | 63 | 3 |
| | | | Very High | >95th Percentile | >256 | 14 | 34 | 10 | 10 | 15 | 21 | 6 | 17 | 5 | 66 | 3 |
| | | 2014 | Very Low | <5th Percentile | <19 | 1 | - | 1 | 1 | 1 | 1 | 0 | 59 | 7 | 32 | 0 |
| | | | Low | <25th Percentile | <44 | 6 | 0 | 1 | 2 | 1 | 2 | 1 | 61 | 6 | 31 | 1 |
| | | | Moderate | 25th - 75th Percentile | 44-124 | 36 | 8 | 10 | 9 | 8 | 11 | 4 | 44 | 3 | 41 | 4 |
| | | | High | >75th Percentile | >124 | 43 | 36 | 9 | 14 | 15 | 7 | 7 | 19 | 1 | 63 | 5 |
| | | | Very High | >95th Percentile | >234 | 14 | 47 | 10 | 13 | 14 | 3 | 8 | 16 | 1 | 67 | 4 |
| | | 2012 | Very Low | <5th Percentile | <22 | 1 | 2 | 1 | 1 | 2 | - | 0 | 64 | 5 | 30 | 0 |
| | | | Low | <25th Percentile | <48 | 6 | 4 | 3 | 1 | 2 | 1 | 1 | 64 | 5 | 29 | 1 |
| | | | Moderate | 25th - 75th Percentile | 48-145 | 36 | 11 | 8 | 9 | 8 | 8 | 3 | 42 | 3 | 47 | 2 |
| | | | High | >75th Percentile | >145 | 45 | 9 | 14 | 14 | 14 | 26 | 5 | 17 | 1 | 71 | 2 |
| | | | Very High | >95th Percentile | >268 | 13 | 11 | 17 | 10 | 13 | 34 | 5 | 14 | 1 | 75 | 2 |
| | | 2011 | Very Low | <5th Percentile | <21 | 1 | - | 1 | 13 | 0 | 1 | 1 | 56 | 5 | 34 | 1 |
| | | | Low | <25th Percentile | <47 | 7 | 0 | 3 | 9 | 2 | 2 | 1 | 58 | 5 | 32 | 1 |
| | | | Moderate | 25th - 75th Percentile | 47-124 | 37 | 10 | 7 | 11 | 10 | 12 | 6 | 36 | 3 | 44 | 4 |
| | | | High | >75th Percentile | >124 | 42 | 18 | 26 | 6 | 11 | 5 | 7 | 25 | 3 | 56 | 4 |
| | | | Very High | >95th Percentile | >218 | 13 | 20 | 33 | 4 | 11 | 2 | 8 | 23 | 2 | 59 | 4 |

Hourly $PM_{10}$ concentrations in 2015 at site 49 were as high as 700 µg $m^{-3}$ and the 'very high' $PM_{10}$ concentrations above the 95$^{th}$ percentile (256 µg $m^{-3}$) contributed 14% to the $PM_{10}$ annual average (Figure 4.11a and Table 4.3) and were higher than at the roadside site 16 (compared to 110.0 µg $m^{-3}$ and contributed 12%) in Bangkok. These 'very high' $PM_{10}$ concentrations occurred across the winter months, for example, in January (34%), December (21%), and November (15%) while the lowest hourly $PM_{10}$ concentrations occurred in September (Figure 4.11b). Diurnal variation showed the 'very high' (the red line, concentration above 256 µg $m^{-3}$) $PM_{10}$ concentrations to occur mainly during the morning rush hour (33% of the very high concentration occurred during these hours) and to a lesser extent during the evening rush hour (20%). The lowest hourly $PM_{10}$ concentrations ((the blue line, concentration below 23 µg $m^{-3}$)) tended to occur both at night and in the middle of the day and the moderate concentrations (the grey line, concentration between 45 -124 µg $m^{-3}$)) occurred more evenly throughout the day (Figure 4.11c and 4.12). The local emission sources of the particulate matter are specific in this industrial area (PCD, 2015). The emissions were often released from the vents of industrial factories and spread out from the crushing processes in stone mills (PCD, 2015), including local transportation.

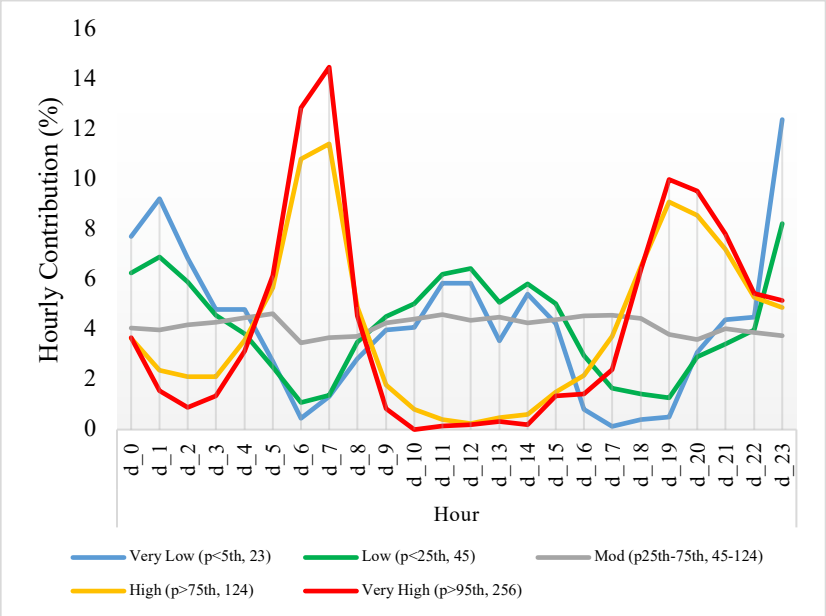
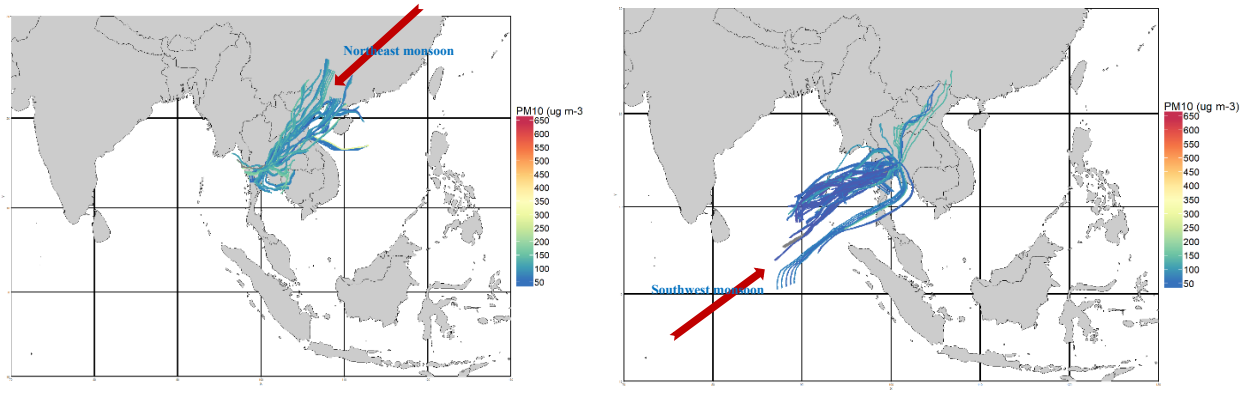



**Figure 4.12:** The percentage of hourly $PM_{10}$ concentrations in different ranges ('very high' $PM_{10}$ concentrations above the 95$^{th}$ percentile; 'high' above 75$^{th}$ percentile, 'moderate between 25 and 75$^{th}$ percentile, 'low' below the 25$^{th}$ percentile, and 'very low' below the 5$^{th}$ percentile) that occurred during different hours of the day at Site 49, central Thailand in 2015

Figure 4.13 shows the 4-day back trajectory air masses had a similar pattern as at site 16, with trajectories during winter months arriving from the north east, and from the south west during rainy months.




(a) January (b) September

**Figure 4.13:** Comparison the different of 4-day backward air masses trajectory plots at site 49, Saraburi in 2015 between (a) winter and (b) rainy seasons

The meteorological conditions were also similar to site 16 described above. There was little relationship between hourly temperature and hourly $PM_{10}$ concentrations, but the highest hourly $PM_{10}$ concentrations occurred when the wind speed was relatively low, and hourly $PM_{10}$ concentrations were lower at higher wind speeds. In contrast to Site 49, there was an association between a specific wind direction, and elevated hourly $PM_{10}$ concentrations. Elevated hourly $PM_{10}$ concentrations occurred when the wind direction was between 100 and 150 degrees (i.e. approximately south easterly wind direction). When the wind direction was between 90 and 180 degrees, the average $PM_{10}$ concentration was 131 µg $m^{-3}$ (95% variability: 27-365). Average $PM_{10}$ concentrations were much lower when wind direction was between 0-90 (115.6 µg $m^{-3}$ (95% variability: 36-258)), 180-270 (51.5 µg $m^{-3}$ (95% variability: 16-141)) and 270-360 (66.5 µg $m^{-3}$ (95% variability: 11-147)) degrees. This major road directly adjacent to the monitoring site is south east of the monitoring station location, as are cement factories, approximately 3 - 30 km away from the monitoring site location.

For other 3 years at this site in 2014, 2012 and 2011 that also had sufficient data capture, the contribution patterns were similar to 2015 as shown in supplementary Tables S13-S15 (See Appendix). In general, these years showed a consistent pattern compared to 2015 at this site, but the winter months during which the highest concentrations occurred varied between years. However, in all years the patterns of variation in hourly $PM_{10}$ indicated that local emission sources made a large contribution to determining elevated annual $PM_{10}$ concentrations, exceeding the annual Thai $PM_{10}$ standard.

#### 4.3.2.2 Moderate concentrations of annual average $PM_{10}$

The sites with moderate annual average $PM_{10}$ concentrations (30-50 μg $m^{-3}$) between 2011 and 2015 were 15 general sites, 6 sites in Bangkok and 9 sites in central Thailand. Two example sites are site 6 at National Housing Authority Klongchan in Bangkok and site 24 at Residence for Department of Primary Industries and Mines in Samut Prakan, central Thailand. At these sites, 2011-2015 annual average $PM_{10}$ concentrations were 35.2 μg $m^{-3}$ and 41.4 μg $m^{-3}$, respectively. This was 26% and 39% of sites in Bangkok and central Thailand with moderate annual average $PM_{10}$ concentrations as shown in Table 4.4 and Table S12 (See Appendix).

**Table 4.4:** Moderate annual average $PM_{10}$ concentrations across central Thailand (μg $m^{-3}$)

| Site | Category | Province | Region | 2011 | 2012 | 2013 | 2014 | 2015 | 2011-2015 | Level |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | General | Bangkok | Central | - | 37.2 | 41.3 | 36.8 | - | 38.4 | Moderate |
| 2 | General | Bangkok | Central | - | - | 52.7 | 51.4 | 42.0 | 48.7 | Moderate |
| 6 | General | Bangkok | Central | 28.0 | 25.8 | | 47.0 | 39.8 | 35.2 | Moderate |
| 7 | General | Bangkok | Central | 40.4 | 43.9 | 42.1 | 40.4 | 33.7 | 40.1 | Moderate |
| 8 | General | Bangkok | Central | - | - | 49.7 | 48.2 | 44.7 | 47.5 | Moderate |
| 18 | General | Bangkok | Central | - | - | 42.3 | 39.2 | 50.2 | 43.9 | Moderate |
| 19 | General | Nonthaburi | Central | 45.2 | 44.8 | 47.6 | 50.3 | 46.3 | 46.8 | Moderate |
| 20 | General | Nonthaburi | Central | 29.1 | 29.3 | 41.5 | 40.5 | - | 35.1 | Moderate |
| 22 | General | Samut Prakan | Central | 52.7 | 32.8 | 22.1 | - | - | 35.9 | Moderate |
| 23 | General | Samut Prakan | Central | - | 45.3 | 48.1 | 54.8 | 47.2 | 48.9 | Moderate |
| 24 | General | Samut Prakan | Central | 47.0 | 43.0 | 40.2 | 40.8 | 35.8 | 41.4 | Moderate |
| 26 | General | Samut Prakan | Central | 44.1 | 39.8 | 42.8 | 45.3 | 39.5 | 42.3 | Moderate |
| 27 | General | Samut Sakhon | Central | 25.6 | - | 53.7 | 57.4 | 45.2 | 45.5 | Moderate |
| 48 | General | Ratchaburi | Central | 41.1 | 31.3 | 24.5 | - | - | 32.3 | Moderate |
| 51 | General | Phra Nakhon Si Ayutthaya | Central | 40.0 | - | 55.7 | 55.1 | 49.1 | 50.0 | Moderate |

The conditions producing annual average $PM_{10}$ concentrations at site 6 in Bangkok for the year 2015 are shown in Figure 4.14 and Table 4.5. Hourly $PM_{10}$ concentrations in 2015 at site 6 were as high as 250 μg $m^{-3}$ and the 'very high' $PM_{10}$ concentrations above the 95$^{th}$ percentile (90 μg $m^{-3}$) contributed 13% to the $PM_{10}$ annual average (Figure 4.14a). These very high $PM_{10}$ concentrations mainly occurred in January (60%) and February (26%), while the lowest hourly $PM_{10}$ concentrations occurred in September (Figure 4.14b). In terms of daily variation, the morning rush hour period (36%) had a larger proportion of 'very high' concentrations above 90 μg $m^{-3}$ compared to the evening rush hour (6%). The lowest hourly $PM_{10}$ concentrations generally occurred at night time (Figure 4.14c). The 4-day back trajectory air masses that arrived during the 'very high' concentrations spent most of the time on average 58% over Thailand before they arrived at this site, and most of the rest of the time over the ocean (22%). The back trajectories spent small proportions of this time over Cambodia (5%), Laos (8%) and Vietnam (4%) as shown in Figure 4.14d. This indicates that the highest hourly $PM_{10}$ concentrations tended to occur when air masses travelled from the east and over Thailand prior to arrival at this site. In contrast, lower hourly $PM_{10}$ concentrations spent more time over the ocean, less time over Thailand, but more time over Myanmar (although the proportion of time was still relatively small) prior to arrival at the site. This indicates that low hourly $PM_{10}$ concentrations tend to occur when trajectories travel from the west prior to arrival at the site as same as the high concentrations of annual average $PM_{10}$.

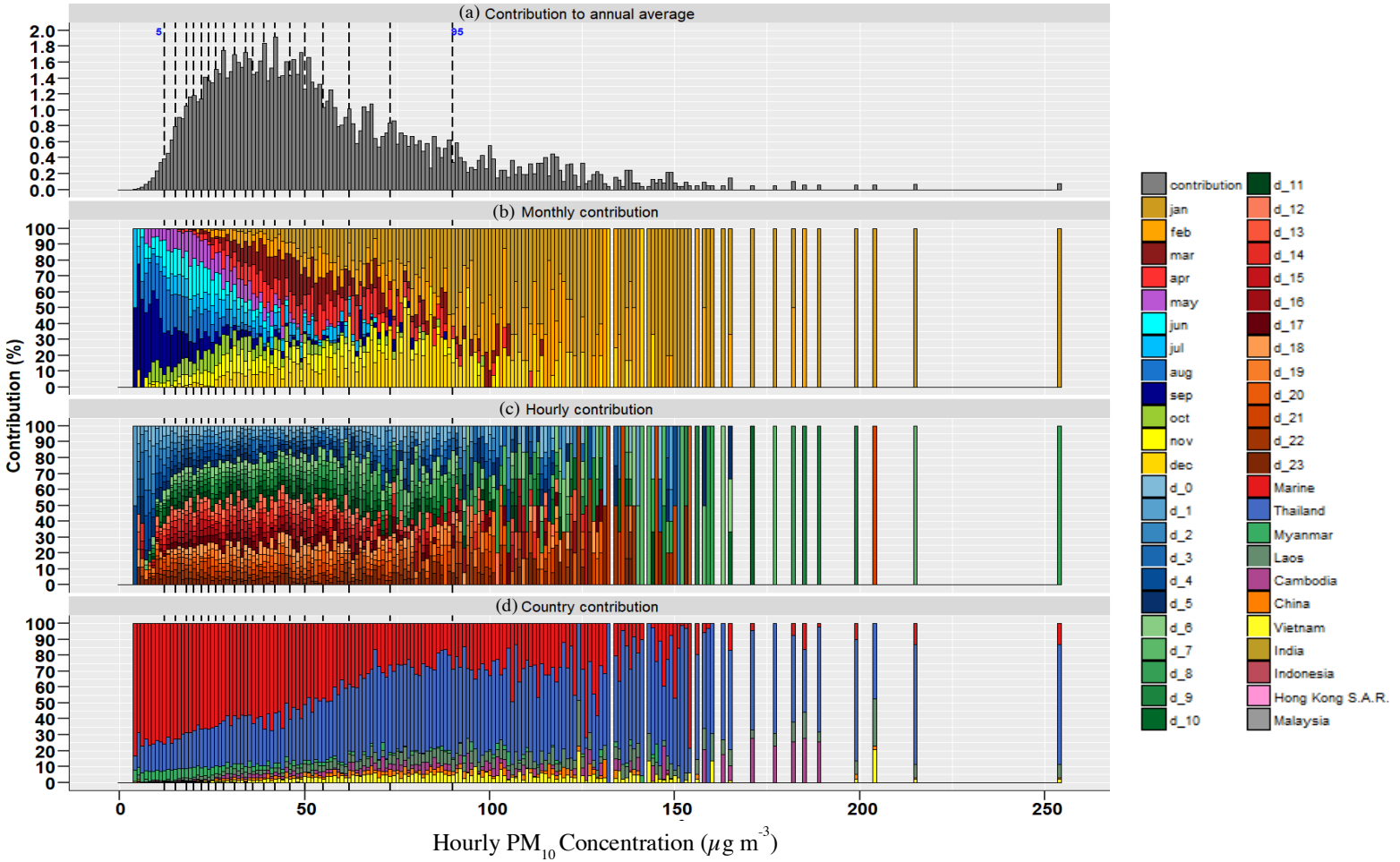



**Figure 4.14:** The different conditions producing annual average $PM_{10}$ concentrations at general site in Bangkok (site 6) in 2015

**Table 4.5:** Comparison of the main conditions producing medium annual average $PM_{10}$ concentrations

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | Country Contribution (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Oct | Nov | Dec | Cambodia | Laos | Marine | Thailand | Vietnam |
| **Bangkok (site 6)** | General site | 2015 | Very Low | <5th Percentile | <12 | 1 | - | - | 5 | 2 | 2 | 0 | 1 | 75 | 17 | 0 |
| | | | Low | <25th Percentile | <22 | 8 | - | 0 | 7 | 4 | 1 | 0 | 1 | 73 | 19 | 0 |
| | | | Moderate | 25th - 75th Percentile | 22-50 | 37 | 4 | 7 | 9 | 10 | 8 | 2 | 3 | 60 | 28 | 2 |
| | | | High | >75th Percentile | >50 | 41 | 48 | 22 | 1 | 4 | 14 | 4 | 7 | 26 | 55 | 4 |
| | | | Very High | >95th Percentile | >90 | 13 | 60 | 26 | 0 | 1 | 11 | 5 | 8 | 22 | 58 | 4 |
| **Samut Prakan (Site 24)** | General site | 2015 | Very Low | <5th Percentile | <10 | 1 | - | 0 | 9 | 0 | 1 | 0 | 0 | 75 | 18 | 0 |
| | | | Low | <25th Percentile | <20 | 7 | 0 | 1 | 8 | 2 | 1 | 0 | 0 | 75 | 17 | 0 |
| | | | Moderate | 25th - 75th Percentile | 20-45 | 38 | 5 | 7 | 9 | 10 | 8 | 2 | 3 | 62 | 27 | 2 |
| | | | High | >75th Percentile | >45 | 42 | 36 | 26 | 4 | 5 | 19 | 5 | 7 | 24 | 58 | 3 |
| | | | Very High | >95th Percentile | >79 | 12 | 40 | 31 | 3 | 3 | 19 | 5 | 7 | 20 | 62 | 3 |

Similar patterns were also seen for 2014 at site 6. However, 2012 was different from these two years. The lowest concentrations occurred across the day and there were small peaks in the morning rush hour and large peaks in the afternoon and evening rush hour. The very high concentrations did not occur mainly in January but occurred across many months for the whole year (See Appendix, Tables S13-S15). In summary, these 3 years at site 6 with substantially different frequencies of high $PM_{10}$ concentrations indicates that it was local emission sources that determined hourly $PM_{10}$ concentrations rather longer-range transport.

Another site is Samut Prakan (site 24) in 2015, situated in central Thailand. Hourly $PM_{10}$ concentrations in this year were as high as 300 μg $m^{-3}$ and the 'very high' $PM_{10}$ concentrations above the 95$^{th}$ percentile (79 μg $m^{-3}$) contributed 12% to the $PM_{10}$ annual average (Figure 4.15a). These very high concentrations also occurred in many months as was the case for site 6 (Figure 4.15b and Table 4.5), but the concentrations in January (40%) were smaller than site 6 (60%) in Bangkok, while the lowest concentrations occurred in September. In terms of daily variation, the morning rush hour (20%) had a larger proportion of 'very high' concentrations above 79 μg $m^{-3}$ compared to the evening rush hour (9%) (Figure 4.15c). The 4-day back trajectory air masses during the 'very high' concentrations that arrived this site spent most of the time on average 62% over Thailand before they arrived at this site, and most of the rest of the time over the ocean (20%). The back trajectories also spent small proportions of this time over neighbouring countries in Cambodia, Laos and Vietnam as shown in Figure 4.18d. However, lower hourly $PM_{10}$ concentrations spent more time over the ocean, less time over Thailand (Figure 4.15d).

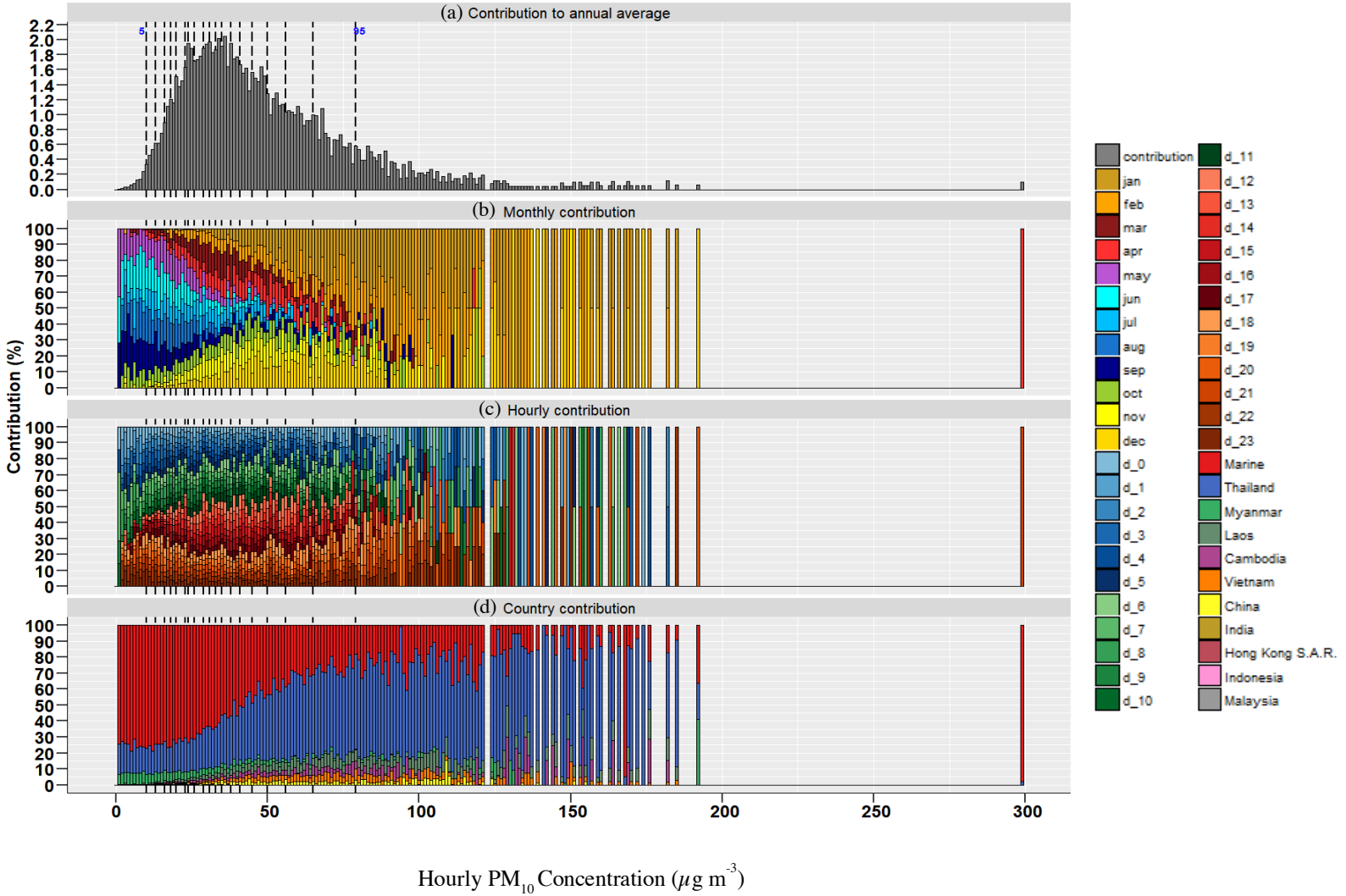



**Figure 4.15:** The different conditions producing annual average $PM_{10}$ concentrations at general site in Samut Prakan (site 24), central Thailand in 2015

In 2013 and 2014 similar patterns were seen at this site (See Appendix, Tables S13-S15) but in 2012 the very high concentrations occurred mainly in several months with highest amount in March (23%). These very high concentrations occurred more often during the day and showed high peaks in the evening rush hour.

In summary, the differences between sites with moderate and high concentrations of annual average $PM_{10}$ from the results described above show the levels of $PM_{10}$ concentrations at $95^{th}$ percentile contributed to annual average are lower than high concentrations and the locations are also further from main road. However, high concentrations at Dingdaeng roadside site (site 16) located across one of the busy roads with high traffic density and congestions in inner Bangkok city, and for central Thailand, a representative site (site 49) located in a heavily industrialised area, result in more high concentrations level than moderate sites. The similarities of the diurnal variation patterns are almost the same in monitored sites with peaks occurring during the morning rush hour period of a day that mainly occur during the dry season (mid-October to mid-May).

### 4.3.2.3 Low concentrations of annual average $PM_{10}$

The sites with low annual average $PM_{10}$ concentrations (<30 μg $m^{-3}$) for period 2011 to 2015, were two general sites in central Thailand and Bangkok and one roadside site in Bangkok as shown in Table 4.6.

**Table 4.6:** Low annual average $PM_{10}$ concentrations across central Thailand

| Site | Category | Province | Region | 2011 | 2012 | 2013 | 2014 | 2015 | 2011-2015 | Level |
|---|---|---|---|---|---|---|---|---|---|---|
| 9 | General | Bangkok | Central | - | - | 20.2 | 17.0 | 20.8 | 19.3 | Low |
| 15 | Roadside | Bangkok | Central | 24.1 | - | 22.4 | 21.3 | - | 22.6 | Low |
| 50 | General | Saraburi | Central | 38.9 | 24.2 | 21.2 | 18.4 | 34.1 | 27.4 | Low |

The lowest concentration of annual average $PM_{10}$ between 2011 and 2015 across central Thailand was 19.3 μg $m^{-3}$ at site 9. Figure 4.16 shows hourly $PM_{10}$ concentrations in 2013 were as high as 120 μg $m^{-3}$ and the 'very high' $PM_{10}$ concentrations above the 95$^{th}$ percentile (44 μg $m^{-3}$) contributed 13% to the $PM_{10}$ annual average (Figure 4.16a and Table 4.7) and were lower than at the roadside site 15 (compared to 51 μg $m^{-3}$ and contributed 14%) in 2014 (Figure 4.17a and Table 4.8). These 'very high' $PM_{10}$ concentrations tended to occur across the winter months at both sites during mid-October to mid-February but at site 15 also occurred in May (23%). Diurnal variation showed the 'very high' $PM_{10}$ concentrations to occur mainly during the morning rush hour (23% at site 9 and 25% at site 15) and to a lesser extent during the evening rush hour (4% at site 9 and 11% at site 15), and occurred more during night time.

The 4-day back trajectory air masses at site 9 show that during hours when very high hourly $PM_{10}$ concentrations are measured, air masses spent a large portion of time over Thailand (69% on average), the ocean (18%), but also over Laos, Myanmar, and Vietnam prior to arrival at the site, as shown in Figure 4.16d and Table 4.7. In contrast, at site 15, air masses at spent a large portion of time over the ocean (50%) but less time over Thailand (42% on average) and some time over neighbouring countries as shown in Figure 4.17d and Table 4.8.

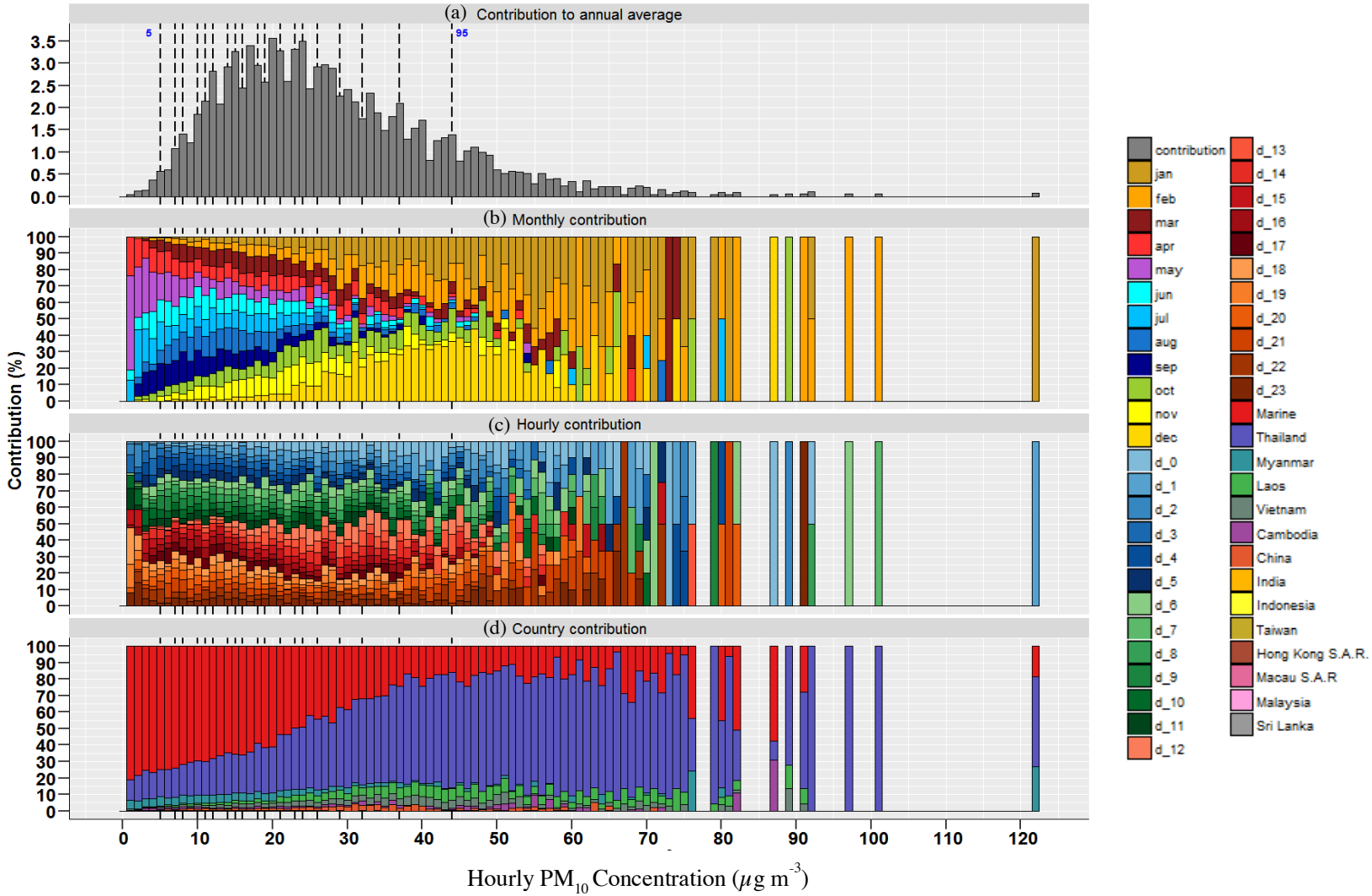



***Figure 4.16:*** *The different conditions producing annual average $PM_{10}$ concentrations at general site in Bangkok (site 9) in 2013*

**Table 4.7:** Comparison of the main conditions producing low annual average $PM_{10}$ concentrations

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | Country Contribution (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration (µg $m^{-3}$) | | Jan | Feb | Mar | Oct | Dec | Laos | Marine | Myanmar | Thailand | Vietnam |
| Bangkok (site 9) | General site | 2013 | Very Low | <5th Percentile | <5 | 1 | 0 | 1 | 1 | 2 | - | 0 | 78 | 5 | 15 | 0 |
| | | | Low | <25th Percentile | <11 | 6 | 2 | 3 | 8 | 6 | 1 | 1 | 75 | 5 | 17 | 1 |
| | | | Moderate | 25th - 75th Percentile | 11-26 | 38 | 5 | 6 | 10 | 9 | 4 | 2 | 60 | 4 | 29 | 2 |
| | | | High | >75th Percentile | >26 | 43 | 27 | 26 | 7 | 9 | 20 | 6 | 21 | 2 | 65 | 3 |
| | | | Very High | >95th Percentile | >44 | 13 | 31 | 30 | 7 | 8 | 17 | 6 | 18 | 2 | 69 | 3 |

**Table 4.8:** Comparison of the main conditions producing low annual average $PM_{10}$ concentrations

| Province | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | Country Contribution (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Cambodia | Laos | Marine | Thailand | Vietnam |
| **Bangkok (site 15)** | Roadside site | 2014 | Very Low | $<5^{th}$ Percentile | <3 | 0 | 0 | 10 | 9 | 22 | 30 | 1 | 0 | 75 | 20 | 1 |
| | | | Low | $<25^{th}$ Percentile | <10 | 5 | 1 | 6 | 7 | 11 | 13 | 1 | 1 | 68 | 25 | 1 |
| | | | Moderate | $25^{th}$ - $75^{th}$ Percentile | 10-28 | 36 | 7 | 8 | 8 | 6 | 6 | 1 | 3 | 54 | 34 | 2 |
| | | | High | $>75^{th}$ Percentile | >28 | 44 | 33 | 8 | 12 | 13 | 19 | 3 | 3 | 49 | 41 | 2 |
| | | | Very High | $>95^{th}$ Percentile | >51 | 14 | 37 | 7 | 13 | 13 | 23 | 3 | 2 | 50 | 42 | 1 |

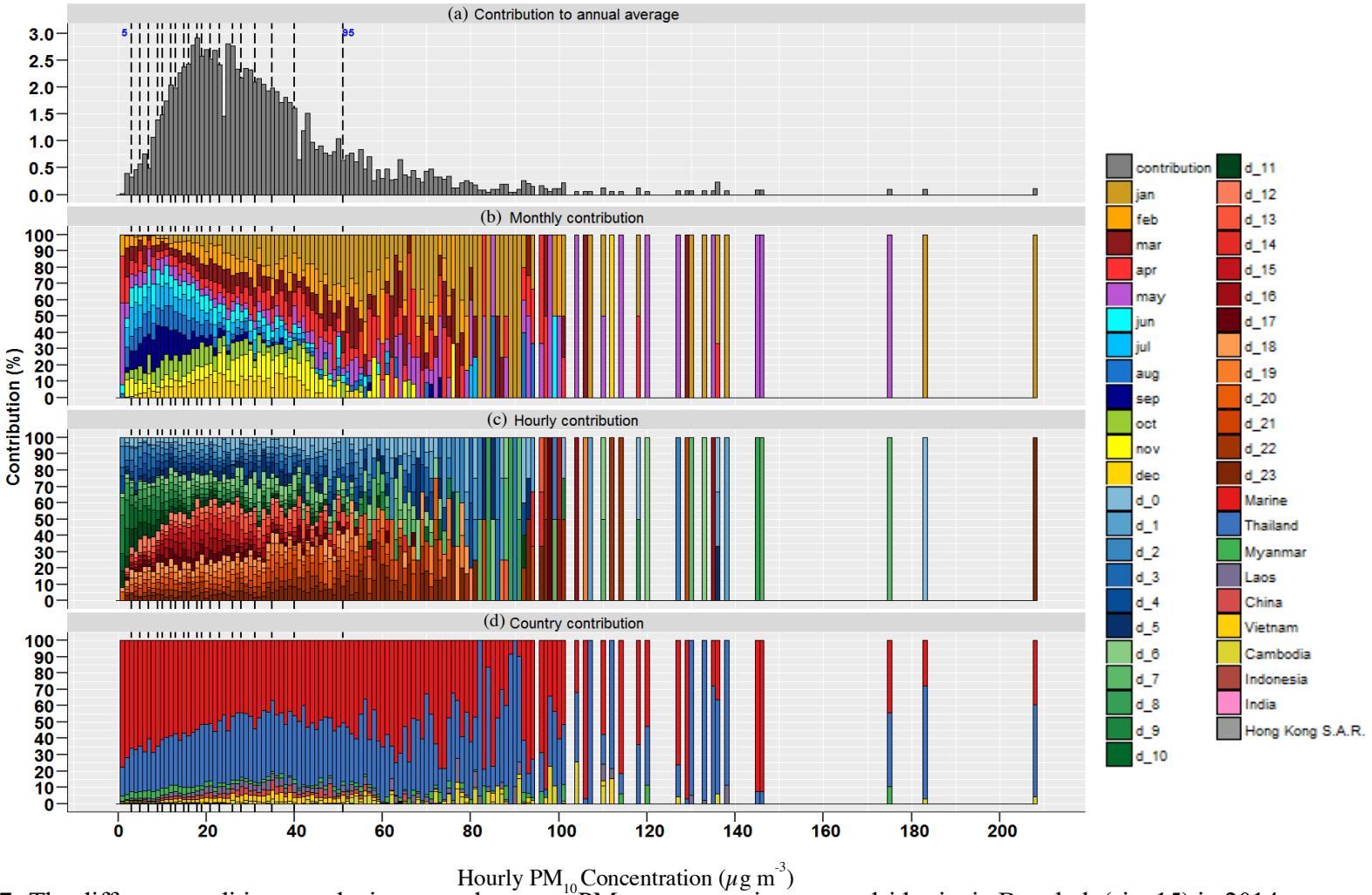



**Figure 4.17:** The different conditions producing annual average $PM_{10}$ concentrations at roadside site in Bangkok (site 15) in 2014

## 4.4 Discussion

This study used the Thailand air pollution monitoring network to investigate the conditions producing annual average $PM_{10}$ concentrations in different areas of Thailand. For central Thailand, including Bangkok, the variation of annual average $PM_{10}$ concentrations shown in this study had a much wider range across all sites between 2011 and 2015 compared to variation in $PM_{10}$ concentrations at sites in other regions (Northern and southern Thailand, as described in Chapter 3). This wider range of annual average $PM_{10}$ concentrations results from sites that have substantial local emission sources that contribute to a greater frequency of high hourly $PM_{10}$ concentrations at specific sites. The predominant emission sources that contributed to sites with the highest annual $PM_{10}$ concentrations in Bangkok and central Thailand were heavy industry and road transport. In Bangkok and central Thailand, annual $PM_{10}$ concentrations were lower at general sites located further from roadside sites and away from large industrial facilities.

Previous studies identified that during the intensive burning season (November-April) smoke plumes from rice straw burning in Pathumthani (the intensive burning area of the Bangkok Metropolitan Region (BMR)) can be transported to Bangkok following the Northeast monsoon while higher numbers of hotspots were observed during the rice straw burning period (from November to April next year) (Tipayarom and Kim Oanh, 2007). Air pollution levels during the dry months in Bangkok are much higher than the wet months (Kim Oahn et al., 2006). At roadside sites, between 2011 and 2015 the annual $PM_{10}$ concentrations had a much wider range compared to general sites in Bangkok (the only region with roadside sites). In Bangkok, the major contributor to $PM_{10}$ and $PM_{2.5}$ was from traffic (mobile sources and road dust) in both wet and dry seasons (Kim Oanh et al., 2006; Loetkamonwit, 2000). In addition, PM concentrations at three Bangkok mass transit system (BTS) stations showed that the PM concentrations were increasing with the traffic volume under BTS stations whilst with increasing height the PM levels were decreased (Lertphuthipisut, 2004). In addition, Kim Oanh et al. (2013) measured $PM_{2.5}$ at fixed road sites, and with mobile monitors along transport routes that included congested urban areas and less congested sub-urban areas. The results showed that $PM_{2.5}$ levels at the fixed roadside sites were twice as high during the dry season compared to wet season and $PM_{2.5}$ concentrations measured in the urban area during the dry season were 3 times higher than in suburban areas.

These previous studies are consistent with the observations of the conditions producing annual $PM_{10}$ concentrations observed in this study. This study also shows that the majority of high and very high hourly $PM_{10}$ concentrations occur during the dry season, and particularly during rush hour periods, indicating a large contribution from traffic sources in Bangkok at the sites exceeding the Thai national standard.

There are differences when comparing the results obtained in this Chapter to those obtained in Chapter 3. The sites in Bangkok and central Thailand showed less association between air mass back trajectory pathway and hourly $PM_{10}$ concentrations, and high hourly $PM_{10}$ concentrations occurred less during specific parts of the year. It is more local sources in the Bangkok Metropolitan Region (BMR) airshed, such as traffic, industry, and rice straw burning in Pathumthani (the intensive burning area of the BMR that can be transported to Bangkok, that become important. There was also less evidence for the short-term peaks in $PM_{10}$ concentrations than occurred in southern Thailand due to long-range transport occurring at sites in Bangkok and central Thailand.

However, the conditions producing the highest annual $PM_{10}$ concentrations at sites in Bangkok and central Thailand result from a larger contribution of local emission sources, road transport, and industrial facilities such as cement factories. The Thailand air quality monitoring network does not operate any monitoring stations at roadside locations outside of Bangkok and central Thailand, and therefore i) the increase in annual $PM_{10}$ concentrations, and ii) conditions producing annual $PM_{10}$ (e.g. contribution from hourly concentrations occurring during rush hour) at road side locations in other parts of Thailand cannot be directly compared with the increase in annual $PM_{10}$ concentrations at roadside sites in Bangkok. However, previous studies have shown that the majority of vehicles in Thailand are registered and used in Bangkok, suggesting that the contribution of road transport emissions to annual $PM_{10}$ concentrations in Bangkok may be larger than in other regions of Thailand. In addition, the other site in central Thailand with elevated annual $PM_{10}$ concentrations was shown to be substantially influenced by local meteorology, consistent with its proximity to local large industrial facilities. The majority of large industrial facilities in Thailand are located in central Thailand, and therefore the conditions resulting in this exceedance of the Thai national standard in central Thailand are likely to be less common than in other regions. However, the lack of sites located in close proximity to industrial facilities in Northern or Southern Thailand prevents an in depth assessment of the contribution of industrial emissions to annual $PM_{10}$

concentrations (and potential exceedance of national air quality standards) in other regions of Thailand.

When taken together, Chapters 3 and 4 show the variety of conditions that contribute to the exceedance of national air quality standards to protect human health in Thailand. The variety of sources, both the source sectors, including biomass burning, road transport and industry, and geographic sources (local and long-range transport) that differ between sites and by region emphasise the need for the development of tailored mitigation strategies to effectively reduce annual $PM_{10}$ concentrations across the whole of Thailand. A mitigation strategy developed for Bangkok is unlikely to have the same effect in Chiang Mai, due to the larger contribution from local emission sources in Bangkok, compared to the large regional contribution of biomass burning emissions to annual $PM_{10}$ in Chiang Mai. The analysis of $PM_{10}$ measurement data in this thesis has shown the value of applying a standard set of statistics to investigate the conditions producing annual $PM_{10}$ concentrations across a country. It has also shown the suitability of the 'chemical climatology' statistics selected for this analysis in disentangling the key contributors of annual $PM_{10}$ concentrations in different parts of Thailand where annual $PM_{10}$ is determined to a different extent by different sources.

# 4.5 Conclusion

On average between 2011 and 2015, in Bangkok, which had both general and roadside sites, there was greater variation in $PM_{10}$ concentrations across roadside sites compared with general sites. The highest annual $PM_{10}$ concentrations were at roadside site in Bangkok and general site in central Thailand. Across sites between 2011 and 2015, 5 sites, located at roadsides in Bangkok and general sites in central Thailand, exceeded the national annual $PM_{10}$ standard of 50 $\mu g\ m^{-3}$. While concentrations were lower at other sites, all sites in Bangkok and central Thailand exceeded the WHO ambient annual $PM_{10}$ guideline of 20 $\mu g\ m^{-3}$. Across different types of sites, there was greater variation in annual average $PM_{10}$ concentrations at Bangkok roadside sites compared with across general sites in Bangkok and central general sites. At sites exceeding the national standard, variation in hourly $PM_{10}$ concentrations indicate that large local emission sources result in the elevated annual $PM_{10}$ concentrations, specifically from roadside emissions and/or large industrial sources. At these sites, highest hourly $PM_{10}$

concentrations contributed a substantial percentage to annual average concentrations, and mainly occurred in morning and evening rush hour periods in dry season.

When results from this study are compared to previous studies conducted in Thailand at the same area in Saraburi province, Phetrawech and Thepanondh (2017) assessed the contribution of different sources to $PM_{10}$ concentrations in Saraburi province, the same province that contains Site 49. In the locations where $PM_{10}$ was monitored in Phetrawech and Thepanondh (2017), emissions from mobile sources, in particular road dust resuspension contributed 71% during peak hourly $PM_{10}$ concentrations. This is consistent with local traffic emissions being a large contributor to $PM_{10}$ concentrations at the sites in central Thailand and Bangkok assessed here. In Bangkok area, Kim Oanh et al. (2006) reported that traffic emission, especially from diesel vehicles, biomass open burning during dry season transported from surrounding areas and secondary inorganic particles were the major contributors to $PM_{2.5}$. Another study conducted in the Bangkok Metropolitan Region by comparing two sites representing an urban residential area in Bangkok, and a suburban/background residential area in Pathumthani province. The results showed that $PM_{2.5}$ and $PM_{2.5–10}$ concentrations in Bangkok were significantly higher than the in Pathumthani (suburb/background) and the major sources for $PM_{2.5}$ were traffic and biomass burning (50–70% of total fine particles), and dust soil and construction soil (60–70% of total coarse particles) for $PM_{2.5–10}$ Wimolwattanapun et al. (2011).

In contrast, sites with low concentrations had a lower frequency of these highest hourly concentrations. The local emission sources therefore play a major role in determining the elevated annual $PM_{10}$ concentration. Therefore, to reduce annual average $PM_{10}$ from sites exceeding the national $PM_{10}$ standard, should focus on reducing peak hourly concentrations from local emissions sources for road transport at Bangkok roadside sites and industrial plants (crushing processes in stone mills, mining, cement etc.) at central general sites. The local maps of site, for example, at Bangkok roadside site and central general site are shown in Figure 4.18.

(a) Bangkok roadside site (Site 12)


https://www.google.com/maps/place/Chulalongkorn+Hospital/@13.7294571,100.5365399,3a,43.5y,3.16h,93.46t/data=!3m6!1e1!3m4!1s4gS5rqWesO7cj21C4eh4Lg!2e0!7i16384!8i8192!4m8!1m2!2m1!1sChulalongkorn+Hospital!3m4!1s0x30e29f290f32d35d:0x79a995799ed40d64!8m2!3d13.730981!4d100.5370084

(b) Central general site (Site 49: Saraburi)


https://www.google.com/maps/place/Na+Phralan+Police+Station/@14.685947,100.8720319,3a,75y,195.78h,92.39t/data=!3m6!1e1!3m4!1sEzqSe094miJIAQIPFPqDKA!2e0!7i16384!8i8192!4m12!1m6!3m5!1s0x311de3f25f95a597:0xf80ee3413818ea92!2sNa+Phralan+Police+Station!8m2!3d14.6863407!4d100.8711145!3m4!1s0x311de3f25f95a597:0xf80ee3413818ea92!8m2!3d14.6863407!4d100.8711145

**Figure 4.18:** Local maps in (a) Bangkok roadside site (Site 12) (b) Central general site (Site 49)

# Chapter 5:

## Sources of $PM_{2.5}$ relevant emissions, atmospheric concentrations and strategies for the mitigation of health impacts in Thailand: A modelling study for 2010 to 2030

## 5.1 Introduction

The monitoring of air pollutant concentrations across Thailand, as described in Chapters 3 and 4, has shown that the Thai National Ambient Air Quality Standards for the protection of human health are exceeded in some locations, and there is exceedance of the World Health Organization Guidelines (WHO) for air pollution concentrations across the whole country. The measurement of $PM_{10}$ concentrations allows for the identification of major sources (which included road transport, industry and biomass burning in different parts of Thailand), exceedance of standards (which is widespread in northern Thailand for annual $PM_{10}$ and also occurred at sites in central Thailand between 2011 and 2015) and assessment of long-term trends.

However, the assessment of monitoring data is limited to understanding the current contribution of sources to current levels of air pollutant concentrations. It does not allow for the assessment of how future changes in emissions are likely to impact future concentrations of air pollutants, including annual average PM concentrations. Therefore, while the analysis of $PM_{10}$ measurement data across Thailand has provided valuable insights into the strategies and sources that need to be targeted to reduce annual PM concentrations, the picture is incomplete because of changes that are expected to occur in Thailand that have the potential to affect PM and PM-precursor emissions, and therefore PM concentrations. Firstly, the UN Population Division estimates that between 2010 and 2030, the population of Thailand is expected to increase by 3 million people (5%). Since 2010, Thailand's GDP has grown between 1 and 8% per year. If this continues, without the implementation of policies to shift away from fossil fuel consumption, then the increased population and socioeconomic development of Thailand has the potential to

substantially increase emissions in Thailand. Therefore, to assess how the annual PM concentrations assessed in Chapters 3 and 4 using measurement data can be reduced in the future, it is necessary to use appropriate modelling methodologies to assess how emissions are expected to change in response to these socio-economic trends, and also to evaluate the effect of implementing different policies, regulations and mitigation measures that are designed to reduce emissions to assess what strategies would be most effective to achieve Thailand's air quality goals. Therefore, measurement for the assessment of current and historical air pollution levels is often complemented by air pollution modelling to assess how these levels are likely to change into the future (U.S. EPA, 2012b).

Many different types of air pollution modelling have been developed to achieve specific tasks in assessing future projections of air pollution levels within a country (Garaga, Kumar Sahu and Harsha Kota, 2018; Leelőssy, *et al.*, 2014; El-Harbawi, 2013). Modelling of the intensity of emissions from different sources within an emission inventory allows projections to be made of how emissions are likely to change in the future from their current intensity (Vongmahadlek *et al.*, 2009). Modelling the atmospheric transport and chemical transformation of pollutants in the atmosphere allows the effect of these emissions on air pollutant concentrations to be estimated, and the change in concentrations in response to changes in emissions (or other drivers such as climate) to be evaluated (Leelőssy, *et al.*, 2014). The different models and tools used to model emissions and air pollution concentrations vary in complexity. Emission inventory methodologies, such as those documented by the IPCC, have three tiers of complexity. 'Tier 1' methods are the simplest and require the least amount of data, while 'Tier 3' methods give the most accurate estimate of emissions but require much more specific data to be used (EMEP/EEA, 2016/IPCC, 2006) as shown in Table 5.1. Atmospheric chemistry transport models vary in how explicitly they represented atmospheric chemical and physical processes (Leelőssy, *et al.*, 2014; Anenberg, *et al.*, 2016; Stohl, *et al.,* 2015).

**Table 5.1:** Overview of emission inventory methodologies

| Emission inventory methodologies | Description |
|---|---|
| **Tier 1** | *'The default method'* |
| | - Using default emission factors compiled from scientific literature<br>- Using readily available statistical data on the intensity of processes (activity rates)<br>- Emission factors is a linear relation between the intensity of the process and the resulting emissions<br>- The 'simple' method that is not suitable for estimating emissions for key categories and has the highest level of uncertainty |
| **Tier 2** | '*Tier 2 is similar to Tier 1'* |
| | - More complex method<br>- Using more specific emission factors developed on the basis of knowledge of the types of processes and specific process conditions that apply in the country for which the inventory is being developed<br>- Reducing the level of uncertainty<br>- Adequate for estimating emissions for key categories<br>- Country-specific or technology-specific emission factors required to apply Tier 2 approach |
| **Tier 3** | *'The most detailed method'* |
| | - There is a wide range of Tier 3 methodologies<br>- Activity data x emission factor are similar to Tier 2 with a greater disaggregation of activity data and emission factors<br>- Using the latest scientific knowledge |

Source: EMEP/EEA (2019), EMEP/EEA (2016), IPCC (2006)

Thailand is a country with a more limited amount of data to assess changes in air pollution emissions and concentrations than is available in North America and Europe. However, air pollution levels are worse than in many North American and European cities, and therefore it is necessary to be able to evaluate the opportunities to reduce air pollution concentrations and health impacts from implementing different mitigation measures in Thailand.

Studies conducted in the region to date include using the GAINS (Greenhouse Gas Air Pollutant Interactions and Synergies) model (http://gains.iiasa.ac.at) to estimate the emission inventory of $PM_{2.5}$, $PM_{10}$, BC, and OC from on-road transport in Bangkok Metropolitan Region (BMR), Thailand between 2007 and 2015. The result showed that $PM_{2.5}$, $PM_{10}$, BC, and OC emissions from transport sector mainly came from heavy duty trucks (Cheewaphongphan *et al.*, 2017). The Weather Research and Forecasting (WRF) (https://www2.mmm.ucar.edu/wrf/users/download/get_source.html); a meteorology model and Community Multiscale Air Quality (CMAQ); a chemical transport model (https://www.epa.gov/cmaq) modeling systems were used to evaluate the emission control measures from biomass burning of $PM_{2.5}$ and $PM_{10}$ during a smog episode in Phayao, northern Thailand, 2012 (Pimonsree and Vongruang, 2018). The result showed that biomass burning outside of the city increased $PM_{10}$ and $PM_{2.5}$ concentrations within the city 85% and 89% respectively. Junpen, Garivait and Bonnet (2013) estimated emissions from forest fires in Thailand using MODIS active fire product. The WRF–CHIMERE (CHIMERE is a chemical transport model; https://www.lmd.polytechnique.fr/chimere/) model was used to estimate the emissions of BC, $PM_{2.5}$ and $PM_{10}$ from biomass open burning in big SEA cities including Thailand. (Permadi, Oanh and Vautard, 2018). The result showed that biomass open burning influenced $PM_{10}$ and $PM_{2.5}$ emissions while urban activities in big SEA cities influenced BC emission. Vongruang, Wongwises and Pimonsree (2017) used WRF-CMAQ (the two-way coupled meteorology and air quality model; https://www.epa.gov/cmaq/wrf-cmaq-two-way-coupled-model) to assess of fire emission inventories for simulating particulate matter in upper Southeast Asia. The result showed that biomass burning is a major source of PM in Upper Southeast Asia.

The modelling studies above have assessed specific source sectors, or particular areas of Thailand. However, to date there has been no application of a model that estimates emissions for historical and future years across the whole of Thailand covering all major source sectors, to evaluate the most effective ways to improve air quality across the whole

country. A comprehensive model covering all source sectors is needed so that mitigation options in different sectors can be assessed in the context of emissions from all source sectors in the country. This comprehensive modelling approach also allows mitigation options in different source sectors to be evaluated against other relevant mitigation options implemented in other source sectors. Finally, the health impacts of air pollution result from the total exposure to pollutants (e.g. $PM_{2.5}$) which results from a whole range of natural and anthropogenic emissions. It is therefore necessary to quantify the emissions from all these source sectors if the impacts of air pollution on health and the health benefits from the implementation of different mitigation options are to be quantified.

This work develops this comprehensive modelling approach to estimate emissions of all pollutants contributing to annual PM concentrations for historical and future years for the first time. This chapter applies a tool called the Long-Range Energy Alternatives Planning-Integrated Benefits Calculator (LEAP-IBC) (Nakarmi, *et al.*, 2020) at the national scale in Thailand to: 1) investigate the importance of different emission source sectors within and outside Thailand to annual average $PM_{2.5}$ concentration and the potential health impact in Thailand; and 2) develop mitigation scenarios that model the implementation of different mitigation measures to improve air quality in Thailand. The LEAP-IBC tool is used to develop an emission inventory of all relevant air pollutants contributing to $PM_{2.5}$ concentrations in historical years (2010-2017), and projected for a baseline scenario to 2030. Mitigation measures included in current plans and strategies in Thailand are modelled in terms of their potential to reduce emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors. Additional mitigation measures in key source sectors are then modelled to show the additional reduction in emissions that could result from taking these additional actions. The results from this analysis build on the assessment of current and historical air pollution concentrations across Thailand described in Chapters 3 and 4 by evaluating how the concentrations of particulate matter across Thailand are likely to change in the future, and how they can be reduced to protect human health.

The key differences between this analysis and the previous modelling studies conducted in Thailand described above are that: 1) it considers the whole of Thailand and how annual $PM_{2.5}$ concentration will change into the future, compared to previous studies which focused on specific region, e.g. Bangkok; and 2) it characterises the link from the drivers of emissions (e.g. energy consumption, agriculture activities), through to the impact they have on population-weighted annual average $PM_{2.5}$ concentration, allowing

the effect of policies and actions implemented in different source sectors to be evaluated. The key advantage of using LEAP-IBC for this purpose is that it has low initial data requirements with simple accounting principles. At its simplest, emissions can be quantified in LEAP for energy demand and supply sectors by multiplying the total fuel consumption in particular economic sectors (i.e. electricity generation, residential, industry, agriculture, commercial and public services, transport, oil and gas production, processing and distribution) by fuel and sector specific emission factors. Data on fuel consumption in different sectors can be obtained from a national energy balance, which are routinely developed by Ministries of Energy (including in Thailand). Default fuel and sector-specific emission factor databases are maintained by international organisations including IPCC (2006) and EMEP/EEA (2016). In addition, it is possible to increase the complexity of the quantification of emissions if more detail data is available. Greater complexity means that i) sectors are disaggregated into a larger number of sub-sectors, ii) technology and activity-based quantification of emissions is undertaken (e.g. quantifying emissions in the road transport sector in which the vehicle fleet is disaggregated by type, and vehicle technology standard). In contrast, many modelling tools tend to use specific and complex data, requiring relatively high levels of expertise (https://www.energycommunity.org). Thus, the LEAP-IBC tool could be used to help the Thai government to estimate air pollution emissions, build mitigation scenarios, and understand how emission reductions benefit climate and health. The results of this chapter could also provide different emission reduction measures of $PM_{2.5}$ to policy makers for improving air quality and mitigating health impacts in Thailand.

## 5.2 Methods

To investigate the importance of different source sectors to air pollution concentrations in Thailand, and the key mitigation measures that could reduce them, the analysis first developed a historical emission inventory of air pollutants in Thailand covering the years 2010-2017. The pollutants included in this analysis were Particulate Matter with aerodynamic diameter less than 2.5 microns ($PM_{2.5}$), Particulate Matter with aerodynamic diameter less than 10 microns ($PM_{10}$), Black Carbon (BC), Organic Carbon (OC), Ammonia ($NH_3$), Nitrogen Oxides ($NO_x$), Nitrous Oxide ($N_2O$), Sulphur Dioxide ($SO_2$), Carbon Dioxide ($CO_2$), Carbon Monoxide (CO), Methane ($CH_4$) and Non Methane Volatile Organic Compounds (NMVOC). However, only six pollutants namely, $PM_{2.5}$, BC, OC, $NO_x$, $SO_2$ and $NH_3$ were focused on in this study, as they are the main pollutants contributing to annual average $PM_{2.5}$ concentrations in Thailand. All major energy and non-energy source sectors were included in the analysis. Sources were disaggregated based on activity in each sector. Having developed a historical emission inventory as described below in detail in the following section, a baseline projection was then made from 2018-2030 to estimate future emissions based on the continuation of current socioeconomic development in Thailand. Finally, alternative future scenarios were created that reflect the implementation of different mitigation measures, including those in existing plans and strategies in Thailand, and additional mitigation measures not currently being considered, but which target the major source sectors.

The following sections describe the methodology used to estimate emissions for each sector for the historic and baseline scenarios (Section 5.2.1), including the activity data and emission factors used, and the mitigation measures that were modelled (Section 5.2.2), including the assumptions that were used to represent them.

## 5.2.1 Emission calculations

Emissions were calculated for three different broad source sector categories, energy demand, energy transformation, and non-energy sectors using the LEAP tool (see Chapter 2). The activity data needed to characterize each source sector differs, as do the assumptions about how the source sector will develop into the future. The sub-sections below describe the methodology used to calculate emissions for each source sector, as well as the source of data, and the assumptions used to develop the baseline scenario. These are summarized in Tables 5.2, 5.3 and Appendix (Table S22 – S36).

**Table 5.2:** Activity data

| Sector | Activity data (2010-2017) | Reference |
|---|---|---|
| Transport | 1. Number of vehicle-km[2] [1]<br><br>*Number of vehicle-km[2] = Average distance travelled x Number of vehicles*<br><br>*Split by:*<br>1) Vehicle type: Road transport (Passenger cars, pickup, van, taxi, three wheelers, motorcycles, truck and bus<br>2) Fuel: Gasoline, diesel, LPG, CNG, electric, hybrid and other<br>3) Emission standard: Euro I - Euro VI<br><br>2. Total fuel consumption[1]<br>*Split by:*<br>1) Vehicle type: Rail, domestic aviation, domestic shipping, pipelines, other or non-specified<br>2) Fuel: Gas diesel oil, electricity, aviation gasoline, heavy fuel oil | [1] Department of Land Transport (DLT);<br>(DLT, 2010-2017) |
| Residential | Total fuel consumption[2]<br>1. Cooking<br>- LPG<br>- Traditional Stove Charcoal<br>- Traditional Stove Wood<br>- Traditional Stove Vegetal Wastes<br><br>2. Lighting<br>- Electricity<br><br>3. Other | [2] Department of Alternative Energy Development and Efficiency (DEDE);<br>(DEDE, 2010-2017) |
| Industry | Total fuel consumption[2] | [2] Department of Alternative Energy Development and Efficiency (DEDE);<br>(DEDE, 2010-2017) |
| Commercial and Public Services | Total fuel consumption[2] | [2] Department of Alternative Energy Development and Efficiency (DEDE);<br>(DEDE, 2010-2017) |
| Agriculture, Forestry and Fishing | Total fuel consumption[2] | [2] Department of Alternative Energy Development and Efficiency (DEDE);<br>(DEDE, 2010-2017) |
| Energy Industry-Own Use | Total fuel consumption[2] | [2] Department of Alternative Energy Development and Efficiency (DEDE);<br>(DEDE, 2010-2017) |
| Electricity generation | 1. Total electricity generated [2]<br>2. Process share | [2] Department of Alternative Energy Development and |

| Sector | Activity data (2010-2017) | Reference |
|---|---|---|
| | Process share = % electricity generated using by different type of power stations<br>3. Process efficiency<br>Process efficiency = % fuel needs to generate electricity<br>4. Domestic electricity demand + exports –imports [2]<br>1) Diesel<br>- Gas diesel oil and heavy fuel oil<br>2. Hydro<br>3. Steam Thermal<br>- Bituminous coal and anthracite, BKB brown coal briquettes, lignite, natural gas, heavy fuel oil, gas diesel oil, biomass, municipal waste, gas and liquids from biomass and wastes<br>4. Gas Turbine<br>- Natural gas and gas diesel oil<br>5. Combined cycle<br>- Natural gas and gas diesel oil<br>6. Cogeneration<br>- Bituminous coal and anthracite, BKB brown coal briquettes, natural gas, heavy fuel oil, biomass, municipal waste, gas and liquids from biomass and wastes<br>7. Gas Engine<br>- Natural gas, biomass, gas and liquids from biomass and wastes<br>8. Renewables | Efficiency (DEDE); (DEDE, 2010-2017) |
| Oil and Gas Production | - Domestic demand for oil and gas products and imports and exports [2]<br>- Fugitive emissions from oil and gas production and distribution [2]<br>- How much oil and gas are produced | [2] Department of Alternative Energy Development and Efficiency (DEDE); (DEDE, 2010-2017) |
| Vegetation fires | Biomass consumed [3, 4] | [3] The Royal Forest Department (RFD) (RFD, 2018)<br>[4] Food and Agriculture Organization (FAO) (FAO, 2018) |
| Agriculture | 1. Livestock Enteric Fermentation and Manure Management [5]<br>- The activity variable is the number of animals split by dairy cattle, buffalo etc.<br>2. Fertilizer Application [5]<br>- The activity variable is the total fertiliser consumption in tonnes of N<br>3. Agricultural Residue Burning [5]<br>- The activity variable is the total residue burned | [5] Food and Agriculture Organization (FAO) (FAO, 2018) |
| Waste | Total amount of waste burned [6]<br>Municipal<br>- Modern waste incineration plant<br>- Open Burning<br>Industrial and Commercial<br>- Plant with emission controls | [6] Pollution Control Department (PCD) (PCD, 2018) |

**Table 5.3:** Baseline scenario assumptions

| Sector | Activity Level Projection (2018-2030) | Energy Intensity Projection 2018-2030 (%/year) [2] | Reference |
|---|---|---|---|
| Transport | Activity grows proportional to the number of vehicles sold and retirement rates | -0.3 | Cheewaphongphan *et al. (*2017) |
| Residential | Activity grows proportional to Population | 0.1 | Koe et al. (2001) |
| Industry | Activity grows proportional to GDP (3.9% per year1) | Continuation of 2000-2014 trend (-1.6) | World Bank (2018) https://wec-indicators.enerdata.net/energy-intensity.html |
| Commercial and Public Services | Activity grows proportional to GDP (3.9% per year[1]) | 0.8 | World Bank (2018) https://wec-indicators.enerdata.net/energy-intensity.html |
| Agriculture, Forestry and Fishing | Activity grows proportional to GDP (3.9% per year1) | -1.3 | World Bank (2018) https://wec-indicators.enerdata.net/energy-intensity.html |
| Energy Industry - Own Use | Activity grows proportional to GDP (3.9% per year1) | - | World Bank (2018) https://wec-indicators.enerdata.net/energy-intensity.html |
| Electricity generation | Activity grows proportional to domestic electricity demand | - | |
| Oil and Gas Production | Activity grows proportional to demand for oil products and natural gas | - | |
| Vegetation fires | Activity grows proportional to annual average area burned between 2010 and 2017 | - | |
| Agriculture | 1. Livestock Enteric Fermentation and Manure Management<br>- Activity grows proportional to the growth in number of animals (1.4% per year)<br>2. Fertilizer Application<br>- Activity grows proportional to annual fertiliser consumption (0.8% per year)<br>3. Agricultural Residue Burning<br>- Activity grows proportional to annual crop production (1.1% per year) | - | FAO analysis (Alexandratos and Bruinsma, 2012) |
| Waste | Activity grows proportional to population | - | |

#### 5.2.1.1 Energy Demand sectors

### 1) Transport

The transport sector was disaggregated into six sub-sector; (1) road transport (2) rail (3) domestic aviation (4) domestic shipping (5) pipelines and (6) other transport. Road transport emissions were calculated from the number of vehicles multiplied by an average distance travelled for different types of vehicles that were split by vehicle category (passenger cars, pickup, van, taxi, three wheelers, motorcycles, truck and bus ), fuel used and vehicle emission control technology (European standards: Euro I - Euro VI) – specific emission factors for the 6 pollutants. For rail, shipping and domestic aviation, emissions were calculated by multiplying total fuel consumption in each category by source specific emission factors. The historical number of vehicle kilometres and fuel consumption (2010-2017) in the transport sector in Thailand was obtained from the department of Land Transport, Ministry of transport, Thailand (DLT, 2010-2017). The energy intensity in the transport sector rail and aviation was projected to decrease by 0.3% a year based on the continuation of historical (2010-2017) trends (World Energy Council, 2010-2014). Emission factors for 6 air pollutants were taken from default international guidelines which are the international standard that recommended by the Intergovernmental Panel on Climate Change (IPCC) for National Greenhouse Gas Inventories (IPCC, 2006) or European Monitoring and Evaluation Programme (EMEP)/European Environment Agency (EEA) (EMEP/EEA, 2016) for air pollutant emission inventory guidebook as shown in Appendix, Tables S22 and S23.

### 2) Residential

The residential sector was disaggregated into three activities; cooking, lighting and other. The emissions were estimated by each fuel for cooking (LPG, traditional stove charcoal, traditional stove wood and traditional stove vegetal wastes), lighting (electricity) and other (electricity) including technology into the proportion of people who cook using each type of fuel and technology. Then multiplying total fuel consumption from different type of fuels with the specific emission factors for the 6 air pollutants. The historical fuel consumption (2010-2017) in the residential sector was obtained from the energy balance of Thailand (DEDE, 2010-2017). Baseline projections to fuel consumption in the

residential sector were made assuming that activity in this sector links to the population of Thailand (Table 5.3). The energy intensity in the residential sector was projected to increase by 0.1% a year based on the continuation of historical (2010-2017) trends (World Energy Council, 2010-2014). Emission factors were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) for 6 air pollutants as shown in Appendix, Table S24.

## 3) Industry

Industry emissions were estimated for the total industry sector with no disaggregation. Emissions were calculated by multiplying total fuel consumption for each fuel by fuel – specific emission factors for the 6 pollutants. Historical fuel consumption (2010-2017) in the industrial sector in Thailand was obtained from the national energy balance (DEDE, 2010-2017). Baseline projections for fuel consumption in the industry sector were made assuming that activity in industry grows proportional to GDP (Table 5.3). The GDP was estimated to grow at 3.9% a year from 2018 to 2030 based on Thai national official projection of GDP growth (World Bank, 2018). The energy intensity in the industry sector was projected to decrease by 1.6% a year based on the continuation of historical (2010-2017) trends (World Energy Council, 2010-2014). Emission factors for 6 air pollutants were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) as shown in Appendix, Tables S25 – S26.

## 4) Commercial and Public Services

Commercial and public services emissions were estimated for the total commercial buildings and institutional buildings. Emissions were calculated by multiplying total fuel consumption for each fuel by fuel – specific emission factors for the 6 pollutants. Historical fuel consumption (2010-2017) in the commercial and public services sector in Thailand was obtained from the national energy balance (DEDE, 2010-2017). Baseline projections to fuel consumption in the commercial and public services sector were made assuming that activity in commercial and public services grows proportional to GDP (3.9% a year) (Table 5.3). The energy intensity in the commercial and public services sector was projected to increase by 0.8% a year based on the continuation of historical (2010-2017) trends (World Energy Council, 2010-2014). Emission factors for 6 air

pollutants were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) as shown in Appendix, Table S27.

## 5) Agriculture, Forestry and Fishing

Emissions were estimated for the total agriculture, forestry and fishing sectors with no disaggregation. Emissions were calculated by multiplying total fuel consumption for each fuel with fuel specific emission factors for the 6 pollutants. Historical fuel consumption (2010-2017) in the agriculture forestry and fishing sector in Thailand was obtained from the national energy balance (DEDE, 2010-2017). Baseline projections to fuel consumption in the agriculture, forestry and fishing sectors were made assuming that activity in agriculture forestry and fishing grows proportional to GDP (3.9% a year) (Table 5.3). The energy intensity in the agriculture forestry and fishing sector was projected to decrease by 1.3% a year based on the continuation of historical (2010-2017) trends (World Energy Council, 2010-2014). Emission factors for 6 air pollutants were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) as shown in Appendix, Table S28.

## 6) Energy Industry - Own Use

Energy emissions from the energy industry itself were estimated for the petroleum refining (Natural gas LPG and electricity). Emissions were calculated by multiplying total fuel consumption for each fuel with fuel – specific emission factors for the 6 pollutants. Historical fuel consumption (2010-2017) in the energy industry own use sector in Thailand was obtained from the national energy balance (DEDE, 2010-2017). Baseline projections to fuel consumption in the energy industry own use sector were made assuming that activity in industry grows proportional to GDP (3.9% a year) (Table 5.2). The energy intensity in the energy industry own use sector was projected to decrease by 1.6% a year based on the continuation of historical (2010-2017) trends (World Energy Council, 2010-2014). Emission factors for 11 air pollutants were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) as shown in Appendix, Table S29.

#### 5.2.1.2 Energy Transformation Sectors

In energy transformation sectors, electricity generation and oil and gas production in this sector were analysed.

### 7) Electricity Generation

Electricity generation emissions were estimated from the different processes that generated electricity. Emissions were calculated by multiplying domestic electricity demand, exports and imports from each process (diesel, hydro, steam thermal, gas turbine, combined cycle, cogeneration, gas engine and renewables) with specific emission factors for the 6 pollutants. Historical fuel consumption (2010-2017) in the electricity generation in Thailand was obtained from the national energy balance (DEDE, 2010-2017). Baseline projections to electricity generated in the electricity generation were made assuming that activity in electricity generation grows proportional to domestic electricity demand (Table 5.3). Emission factors for 6 air pollutants were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) as shown in Appendix, Table S30.

### 8) Oil and Gas Production

Oil and gas emissions were estimated covering fugitive emissions from oil and gas production and distribution. Emissions were calculated by multiplying domestic demand for oil and gas products and imports and exports with specific emission factors for the 6 pollutants. Historical fuel consumption (2010-2017) in oil and gas production in Thailand was obtained from the national energy balance (DEDE, 2010-2017). Baseline projections to product produced in this sector were made assuming that activity in oil and gas production grows proportional to demand for oil products and natural gas in the demand sector, and the imports and exports (Table 5.3). Emission factors for 6 air pollutants were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) as shown in Appendix, Table S31.

### 5.2.1.3 Non-Energy sectors

#### 9) Vegetation fires

Vegetation fire emissions were estimated for onsite burning of forest and grassland disaggregated into three groups: 1) secondary tropical and subtropical forest; 2) tropical subtropical grasslands excluding savanna burning; and 3) general shrubland. Emissions were calculated by multiplying the total biomass burned (calculated by multiplying the annual area burned (ha/year) by the biomass consumed (kg/ha)) by an emission factor for each pollutant. Historical fuel consumption (2010-2017) in the vegetation fires sector in Thailand was obtained from the Forest Protection and Fire Control Bureau, Royal Forest Department (2010-2017) and FAOSTAT (FAO, 2018). Baseline projections of forest area burned in the vegetation fires assumed that the future burned area was the 2010-2017 average area burned (Table 5.3). Emission factors for 6 air pollutants were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) as shown in Appendix, Table S32.

#### 10) Agriculture

The agriculture sector was disaggregated into three activities: 1) livestock enteric fermentation and manure management; 2) fertilizer application; and 3) agricultural residue burning. The emissions were estimated for each activity and calculated by multiplying: 1) the number of animals split by dairy cattle, buffalo etc.; 2) the total fertiliser consumption in tonnes of N per year; and 3) the total residue burned (based on annual crop production values and residue to crop ratio default factors from EMEP EEA, 2016), respectively with specific emission factors. The historical consumption (2010-2017) in the agriculture sector was obtained from the agricultural statistics of Thailand (Office of Agricultural Economics, 2010-2017) and the Food and Agricultural Organization FAO (FAO, 2018). Baseline projections to livestock enteric fermentation and manure management, fertilizer application, and agricultural residue burning were made assuming that activity in this sector grows proportional to the growth in the number of animals by increase 1.4% per year, annual fertiliser consumption animals by increase 0.8% per year and annual crop production animals by increase 1.1% per year, respectively (Table 5.3) (Alexandratos and Bruinsma, 2012). Emission factors for 6 air pollutants were

taken from default international guidelines that recommended by IPCC (2006), EMEP/EEA (2013) and EMEP/EEA (2016) as shown in Appendix, Tables S33-S35.

### 11) Waste

Waste emissions were estimated from burning the municipal solid waste and industrial commercial waste sector. Emissions were calculated by multiplying total amount of waste burned from municipal (modern waste incineration plant and open burning) and industrial and commercial (plant with emission controls) with specific emission factors for 6 different pollutants. Historical waste generation (2010-2017) in the waste sector in Thailand was obtained from the Thailand Pollution Control Department, Department of Health and Department of Industrial Works (2010-2017). Baseline projections of the total amount waste generated were made assuming that activity in this sector grows proportional to population (Table 5.3). Emission factors for 6 air pollutants were taken from default international guidelines that recommended by IPCC (2006) or EMEP/EEA (2016) as shown in Appendix, Table S36.

## 5.2.2 Mitigation scenarios

Mitigation scenarios were developed that represent the implementation of different policies and measures to reduce air pollutant emissions in Thailand. The emissions and air pollution impacts in the mitigation scenarios were then compared against the emissions and impacts in the baseline scenario to evaluate the extent to which the policies and measures could be effective in improving air quality in Thailand. Two mitigation scenarios were developed. The first represents policies and measures that have already been included in nationally endorsed plans and strategies in Thailand. The second scenario includes additional policies and measures that are not included in national plans, but which target major air pollution source sectors not controlled by existing policies and measures. The 11 mitigation measures included in these two scenarios are described in Table 5.4.

**Table 5.4:** Description of mitigation measures modelled in LEAP analysis to quantify air pollution reductions from their implementation

| Number | Sector | Name of mitigation measures | Target and Timeline | Source of mitigation measure |
|---|---|---|---|---|
| **Existing plans** | | | | |
| Measure 1 | Transport | ▪ Increasing Euro 5 and 6 vehicles standards | ▪ In 2023 all new HDV vehicles added to the vehicle fleet will meet Euro 5 standard<br>▪ In 2023 all new LDV vehicles added to the vehicle fleet meet Euro 6 standard | - Adapted from Thai roadmap for Euro 5/6 standards (Thai Sub-Committee on Emission Standards for Motor Vehicles under Thailand's Pollution Control Board, PCD (2016)) |
| Measure 9 | Vegetation fires | Reducing the number of forest burned areas | ▪ By 2030 the number of hectares of forest burned annually will be reduced to 48,000 hectares compared to 216,000 hectares in 2018 | - National Master Plan for Open Burning Control (PCD, 2010c) |
| Measure 11 | Electricity generation | Increasing renewable energy | ▪ By 2030, 20% of all electricity generated will come from renewable sources | - Thai Existing Policy on Power Development Plan (PDP2015: 2015-2036)<br>- Energy plan (Ministry of Energy, 2015) |
| **Additional plans** | | | | |
| Measure 2 | Residential | ▪ Replacing traditional charcoal stove with clean fuel for cooking | ▪ By 2030, 100% of households currently cooking using charcoal will switch to cooking using LPG | - Additional measure from key source analysis in this study |
| Measure 3 | Residential | ▪ Replacing traditional wood stove with clean fuel for cooking | ▪ By 2030, 100% of households currently cooking using wood will switch to cook using LPG | - Additional measure from key source analysis in this study |
| Measure 4 | Residential | ▪ Replacing traditional vegetal wastes stove with clean fuel for cooking | ▪ By 2030, 100% of households currently cooking using vegetal wastes will switch to cook using LPG | - Additional measure from key source analysis in this study |
| Measure 5 | Industry | ▪ Reducing brown coal briquettes use in industry | ▪ By 2030 the use of brown coal briquettes in industry will be reduced by 50% compared to the baseline scenario | - Additional measure from key source analysis in this study |
| Measure 6 | Industry | ▪ Reducing primary solid biomass use in industry | ▪ By 2030 the use of primary solid biomass in industry will be | - Additional measure from key source analysis in this study |

| Number | Sector | Name of mitigation measures | Target and Timeline | Source of mitigation measure |
|---|---|---|---|---|
| | | | reduced by 50% compared to the baseline scenario | |
| Measure 7 | Agriculture: Agricultural residue burning | ▪ Banning crop residue burning | ▪ By 2030, all crop residue will be removed from fields and used for productive purposes, and there will be zero open burning of crop residue in fields | - Additional measure from key source analysis in this study |
| Measure 8 | Agriculture: Fertilizer application | ▪ Replacing urea with the other complex NK and NPK fertilizers use in agriculture | ▪ By 2030 the use of urea fertilizer will be 100% replaced with other complex NK and NPK fertilizers with reduced ammonia emissions | - Additional measure from key source analysis in this study |
| Measure 10 | Waste | ▪ Banning open waste burning | ▪ By 2030, there will be no open burning of waste at dumpsites or in residential homes | - Additional measure from key source analysis in this study |

## 1) Transport

Vehicle emissions were the main source of PM in Bangkok Metropolitan Region and the effects of reducing the emissions by controlling of fuel and engine standards, the shift in the fuel type used are necessary (Cheewaphongphan *et al.*, 2017). Thailand's Pollution Control Board has developed the roadmap for Euro 5 and 6 fuel quality standards (gasoline and diesel), by increasing all new LDV vehicles meet Euro 5 standard in 2023 and Euro 6 standard in 2029, and increasing all new HDV vehicles meet Euro 5 standard in 2026 and Euro 6 standard in 2032. These are the existing plans that were taken from Thai roadmap for Euro 5 and 6 standards and used to develop the mitigation scenario in the transport sector (Thai Sub-Committee on Emission Standards for Motor Vehicles under Thailand's Pollution Control Board, PCD (2016)). A mitigation measure for this study (Measure 1) was developed that increases the number of all new HDV vehicles added to the vehicle fleet will meet Euro 5 standard by 2023 and all new LDV vehicles added to the vehicle fleet meet Euro 6 standard by 2023, starting in 2018 and completed in 2030.

## 2) Residential

In Thailand, traditional biomass including fuel wood, charcoal, paddy husk and agricultural waste is mainly used as energy because of the unavailability of natural gas in some rural areas. This practise results in substantial air pollutant emissions and exposure both indoors and outdoors. The mitigation measures were therefore developed to replace traditional stove using charcoal (Measure 2), wood (Measure 3), and vegetal wastes (Measure 4) with clean fuel for cooking such as LPG. The targets are by 2030 the number of households cooking with traditional stoves (charcoal, wood and vegetal wastes) will be reduced to zero and replaced with LPG starting in 2018 and completed in 2030, assuming a linear decrease. This is an additional measure that is not included in existing plans in Thailand but which targets a key source sector for primary particulate matter emissions.

Many developed countries have demonstrated that a complete transition away from cooking using solid biomass is feasible, both in urban and rural areas (Bonjour *et al.*, 2013). Globally, the proportion of households cooking using solid fuels decreased from 60% in 1980 to 42% in 2010, showing that it is feasible for large numbers of people to transition from solid biomass to cleaners forms of energy for cooking (Bonjour et al. 2013). This transition has also been shown to be effective at reducing air pollution emissions from residential cooking, including in South Asia. For example, measurement of $PM_{2.5}$ concentrations in household kitchens in Nepal, using four different cooking fuels showed that kitchen $PM_{2.5}$ concentrations when using biomass fuel stoves (656 mg $m^{-3}$) were the most significant sources of $PM_{2.5}$, followed by kerosene (169 mg $m^{-3}$), LPG (101 mg $m^{-3}$) and then electric (80 mg $m^{-3}$) stoves and when compared with electric stoves, use of LPG, kerosene and biomass stoves were associated with increased indoor $PM_{2.5}$ concentrations of 65%, 146% and 733%, respectively (Pokhrel *et al.,* 2015).

## 3) Industry

The industry has been reported for one of the large contributors of PM emissions in areas surrounding Bangkok, including the central and eastern Thailand (Vongmahadlek *et al.,* 2009; Pham, Manomaiphiboon and Vongmahadlek, 2008). The emissions from fuel consumption for industrial processes consisted of NOx, $SO_2$, NMVOC, CO, $NH_3$, OC, and BC that affected air quality in Thailand (Pham, Manomaiphiboon and Vongmahadlek, 2008).

Based on the national energy balance for Thailand in 2017, 36% and 53% of total energy consumed in industry was using brown coal briquettes and primary solid biomass (wood), respectively (DEDE, 2017). There are currently no plans or strategies in Thailand to reduce consumption of these dirty fuels, therefore, a new scenario modelled the effect of reducing their use in industry by 50% (Measure 5 and 6) by 2030, assuming a linear decrease compared to the baseline scenario. Their use was replaced with natural gas to access the effect of action in this sector starting in 2018 and completed in 2030. This is consistent with the changes in the industrial energy consumption that the IEA have identified as being achievable (IEA, 2018).

## 4) Agriculture

The banning of crop residue burning on agricultural fields can be effective at improving air quality because it makes a large contribution to air pollution emissions. Previous studies showed that agricultural burning from crop residues correlated to ambient PM emissions (Phairuang, Hata and Furuuch, 2017; Chandra et al., 2017). The study from Awasthi, *et al.* (2011) found that reducing $PM_{10}$, $PM_{2.5}$ and $PM_{10-2.5}$ concentrations when no crop residue burning period months (background concentrations) were $97 \pm 21$, $57 \pm 15$ and $4 \pm 6$ $\mu g\ m^{-3}$, respectively. In contrast, the $PM_{10}$, $PM_{2.5}$ and $PM_{10-2.5}$ levels increased up to 66, 78 and 71% during rice crop residue burning, and 51, 43 and 61% during wheat crop residue burning, respectively. Another study from Amit Dhir (2015) showed that during paddy harvesting period (stubble burning), there was an increase of 87% and 53% in $PM_{10}$ and $PM_{2.5}$ concentrations, respectively when compared to pre-harvesting period (less stubble burning). However, for post-harvesting period, there was an increase in $PM_{10}$ (67%) and $PM_{2.5}$ (6%) concentrations respectively when compared to pre- harvesting period (a reduction in $PM_{10}$ (11%) and $PM_{2.5}$ (31%) concentration). Thus, from the previous studies mentioned above, one of the feasible mitigation measures for reducing PM emissions in agricultural areas is banning crop residue burning in agricultural fields. Therefore, mitigation measures were developed to ban crop burning (Measure 7) that reduces the fraction burned in field of agricultural residue burning from 25% starting in 2018 and by 2030, all crop residue will be removed from fields and used for productive purposes, and there will be zero open burning of crop residue in fields, assuming a linear decrease.

Ammonia is a precursor gas for secondary inorganic aerosols and plays an increasingly important role in $PM_{2.5}$ concentration (Huang et al., 2014; Tao et al., 2014). The fertilizer application from the agricultural sector shows the largest source of $NH_3$ emissions (Carnell et al., 2017; Xu et al., 2015; Yan et al., 2003) and consequently contributes to $PM_{2.5}$ concentrations (Zhao et al., 2017; Wu et al., 2016) with represents 2–4% of $PM_{10}$ and 9–12% of $PM_{2.5}$ in southern Europe (Querol et al., 2009). Previous studies from Meng, *et al.* (2018) also found that applying urea fertiliser caused extremely high $NH_3$ and $NH_4^+$ concentrations in the North China Plain. A guide to replace urea fertiliser with another nitrogen form could reduce ammonia emissions typically around 20% of total N applied for urea (Newell Price et al., 2011). Thus, from the previous studies mentioned above, the feasible mitigation measure (Measure 8) is to replace urea with the other complex NK and NPK fertilizers for reducing $NH_3$ emission in 2030 (Measure 8) starting in 2018 and by 2030 the use of urea fertilizer will be 100% replaced with other complex NK and NPK fertilizers with reduced ammonia emissions, assuming a linear decrease.

These two measures above are additional measures that are not included in existing plan in Thailand but targets a key source of primary PM emissions, especially during particular times of the year. Alternatives to open burning of crop residues have been demonstrated, such as using the residue for productive purposes like electricity generation, which can be cost-effective, making the transition to no open burning of crop residue feasible (Bhuvaneshwari, Hettiarachchi, and Meegoda, 2019).

## 5) Vegetation fires

This scenario is based on the government target to reduce forest burning outlined in the National Master Plan for Open Burning Control (PCD, 2010c). A mitigation measure (Measure 9) was developed that by 2030 the number of hectares of forest burned will be reduced to 48,000 hectares per year starting in 2018 and completed in 2030, assuming a linear decrease (24% reduction in forest burning).

## 6) Waste

The uncontrolled burning of waste and ineffective management is a global issue occurring in many countries and it has been identified as a significant source of PM (Sharma, *et al.,* 2019; Wiedinmyer, Yokelson and Gullett, 2014; Hodzic, *et al.,* 2012), including the contribution health and environmental impacts from open burning of waste (U.S. EPA, 2012a). The previous studies showed that he emissions of $PM_{10}$ from open waste burning are equivalent to 22% of the total anthropogenic emissions for China (Wiedinmyer, Yokelson and Gullett, 2014). Another study found that in Mexico, 92% of households in rural areas disposed of waste by uncontrolled burning in unofficial dumps (Reyna-Bensusan, Wilson and Smith, 2018). A study in East Delhi, India on an assessment of the MSW Management found that $PM_{10}$ emissions from waste burning increased sharply from 52 MT $PM_{10}$ in 2000 to 1,254 MT $PM_{10}$ in 2044, and drops to zero in 2045 after the expected closure of the disposal site (no open burning is expected on a closed dumpsite) (TERI, 2018). In Thailand, the mitigation efforts on zero waste and zero landfilling have been focussed (PCD, 2019) due to the management of municipal solid waste (MSW) is one of the key problems for urban areas like Bangkok (Sukholthaman, Shirahada and Sharp, 2017).

Thus, a mitigation measure to ban open waste burning (Measure 10) was developed that the amount of open waste burning by 2030, there will be no open burning of waste at dumpsites or in residential homes (reduced to zero from 8,730,000 tonnes per year starting in 2018), assuming a linear decrease. This is additional measure that is not included in existing plan in Thailand. Alternatives to the open burning of waste include implementing improved waste separation, to facilitate recycling, and composting of organic waste, as well as waste to energy schemes to increase electricity generation capacity. These have been demonstrated as being effective at reducing the amount of waste that is openly burned, when combined with expansion of formal waste collection systems (CCAC, 2015).

### 7) Electricity Generation

Electricity generation from natural gas, oil and renewable energy sources has increased in Thailand recently. The shares of final energy consumption by fuels from electricity, renewable energy and traditional renewable energy in Thailand were 20%, 9% and 6%, respectively (Ministry of Energy, 2018). Therefore, based on the Thai official government existing plan on Power Development Plan (PDP2015) between 2015 and 2036 (Ministry of Energy, 2015), one of the key objectives in this plan is to develop renewable energy up to 20%. The mitigation measure to increase renewable energy (Measure 11) was developed to increase renewable energy. The target is increasing 20% of generating capacity from renewable energy sources by 2030, starting in 2018 and completed in 2030, assuming a linear decrease. This is an existing measure that is included in existing plans in Thailand (PDP2015).

## 5.2.3 $PM_{2.5}$ Concentration and health impact assessment modelling

As stated in Chapter 2 (Section 2.3), the LEAP tool was used to estimate emissions of $PM_{2.5}$ and $PM_{2.5}$-precursor emissions for 2010-2030 then converted into population-weighted annual average $PM_{2.5}$ concentrations across Thailand, and associated impacts on premature mortality. In 2010, the difference between emissions of each pollutant, and the future year (2018 – 2030) was calculated. The estimation for number of premature deaths attributable to $PM_{2.5}$ exposure in Thailand was calculated as well. The increased risk of premature mortality for the five disease categories of ischaemic heart disease, cerebrovascular disease, lung cancer, chronic obstructive pulmonary disease and acute lower respiratory infection (in children, other diseases are adults (>30 years old)) were estimated. An exposure level was then estimated for very low concentrations (~5 $\mu g\ m^{-3}$) to very high $PM_{2.5}$ concentrations (10,000 $\mu g\ m^{-3}$) and then the total health burden from a particular population-weighted $PM_{2.5}$ concentration, resulting from a particular set of emissions for a particular year or scenario, estimated.

## 5.3 Results

The results of the emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors (BC, OC, $NH_3$, $NO_x$, and $SO_2$) from different key source sectors averaged between 2010 and 2017 in the energy demand sector, transformation sector and non-energy sector are shown in Table 5.5. The main sources of $PM_{2.5}$ and OC emissions were vegetation fires that emitted 102.7 kt $yr^{-1}$ and 56.9 kt $yr^{-1}$, respectively. The transport sector as the largest source of $NO_x$ (625.2 kt $yr^{-1}$), and BC (27.7 kt $yr^{-1}$) emissions. The agricultural sector was the largest source of $NH_3$ (574.1 kt $yr^{-1}$) emissions and electricity generation emitted $SO_2$ (377.7 kt $yr^{-1}$).

**Table 5.5:** The averages of annual emissions between 2010 and 2017 from different source sectors across Thailand. The highlighted values represent the largest individual emission source of each pollutant between 2010 and 2017.

| Sectors | Emissions (kt $yr^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | **$PM_{2.5}$** | **BC** | **OC** | **$NH_3$** | **$NO_x$** | **$SO_2$** |
| Agriculture | 61.8 | 5.7 | 37.1 | **574.1** | 101.3 | 3.7 |
| Agriculture Forestry and Fishing | 14.0 | 5.8 | 4.1 | 0.02 | 137.7 | 67.4 |
| Charcoal Making | 53.8 | 3.9 | 26.7 | 7.7 | 3.7 | 11.9 |
| Coke Production | 3.7 | 0.7 | 0.5 | 0.001 | 0.001 | 0.001 |
| Commercial and Public Services | 0.03 | 0.001 | 0.01 | 0.1 | 2.6 | 0.04 |
| Electricity generation | 26.4 | 0.8 | 3.1 | 0.1 | 174.6 | **377.7** |
| Energy Industry Own Use | 0.3 | 0.03 | 0.2 | 0.5 | 22.2 | - |
| Industry | 71.8 | 15.3 | 29.1 | 48.9 | 169.1 | 343.2 |
| Oil refining | - | - | - | - | 2.6 | 40.3 |
| Residential | 66.5 | 12.0 | 28.6 | 11.8 | 27.0 | 10.0 |
| Transport | 47.2 | **27.7** | 11.1 | 5.5 | **625.2** | 0.1 |
| Vegetation Fires | **102.7** | 7.5 | **56.9** | 13.5 | 37.1 | 6.7 |
| Waste | 76.3 | 5.1 | 41.0 | 8.8 | 44.6 | 4.3 |
| **Total** | **524.5** | **84.5** | **238.4** | **670.7** | **1,347.8** | **865.3** |

The details of the emissions are divided into 4 parts in different scenarios: 5.3.1 Historical emissions, 5.3.2 Baseline emissions 5.3.3 Mitigation scenarios, and 5.3.4 $PM_{2.5}$ concentration and health impacts as described below.

## 5.3.1 Historical emissions

The historical emissions are estimated based on the actual measured statistical information on each source sector collected for 2010 - 2017 in Thailand (as opposed to the emission estimates from 2018 to 2030 which are based on projections in activity data). $PM_{2.5}$ emissions are classified as both primary emissions emitted directly from sources into the atmosphere, such as on-road vehicles, and secondary emissions that formed from chemical reactions of $SO_2$, $NO_x$, $VOC_s$ and $NH_3$ in the atmosphere. BC and OC are primary emissions that comprise a significant proportion of $PM_{2.5}$ and are formed by incomplete combustion associated with fossil fuels, diesel engines, biomass fuels etc. Therefore, this study focused on the main emission sources with the following details:

### 1) $PM_{2.5}$

The result in Figure 5.1 (see Appendix, Table S16) shows that during the years 2010 to 2017 many major sources contributed to $PM_{2.5}$ emissions. Vegetation fires were the main source of $PM_{2.5}$ emission (except 2011) that contributed with the largest average percentage contribution (20%), followed by the waste sector (15%), industry (14%), residential cooking (13%), agriculture residue burning (12%) and other source sectors from electricity generation, motor vehicles in transport sector and etc. In 2011, the reduction in emission of air pollutants from vegetation fires is consistent with the analysis of monitoring data in northern Thailand which showed substantial (~20%) reductions in annual average $PM_{10}$ concentrations associated with reductions in biomass burning emissions (Chapter 3).

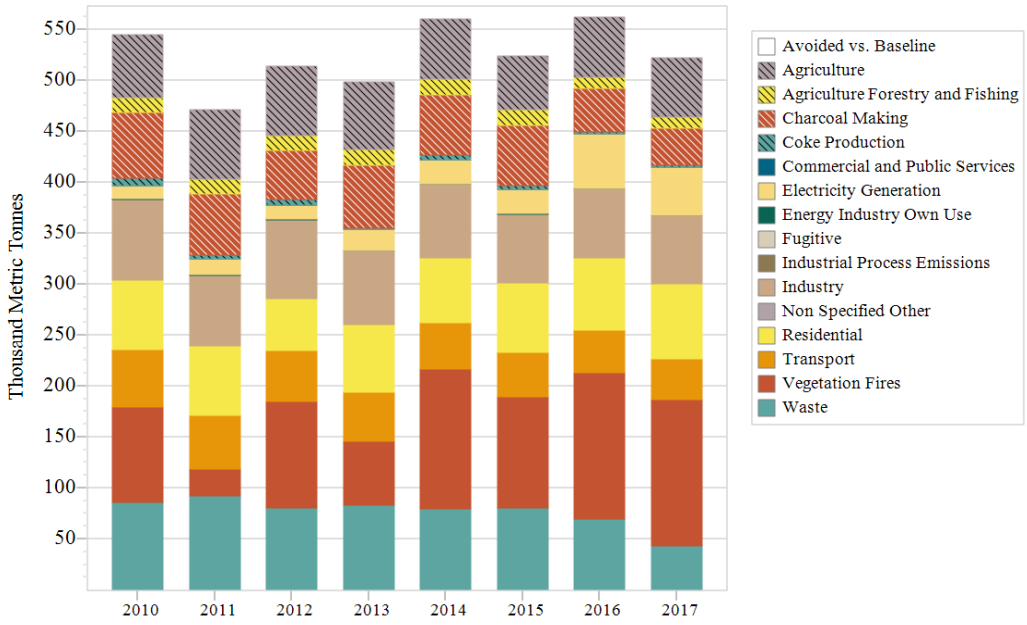



**Figure 5.1:** $PM_{2.5}$ emission from different sources between 2010 and 2017

## 2) BC

BC emission from diesel engine vehicles such as pickup and truck in transport sector led to the largest BC source that contributed 33%, followed by the industry sector (18%), residential (14% - using traditional stove from wood, charcoal, and vegetal wastes for cooking), vegetation fires (9%), agriculture forestry and fishing (7%), agriculture (7%), waste (6%) etc., as shown in Figure 5.2 (see Appendix, Table S17).

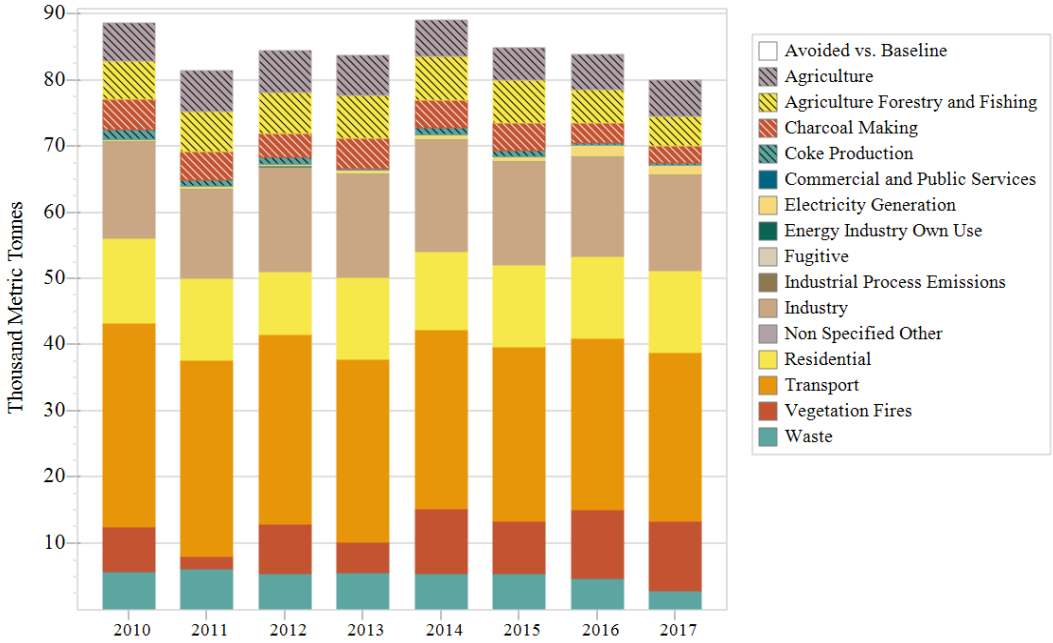



**Figure 5.2:** BC emission from different sources between 2010 and 2017

## 3) OC

OC emission showed similar sources to $PM_{2.5}$ emission, emitted from vegetation fires (averaged 24% - on-site burning of forests and grassland and savanna burning), followed by waste sector (17%), agriculture residue burning (16%), industry (12%), cooking in residential sector (12%), charcoal making (11%) etc., as shown in Figure 5.3 (see Appendix, Table S18).

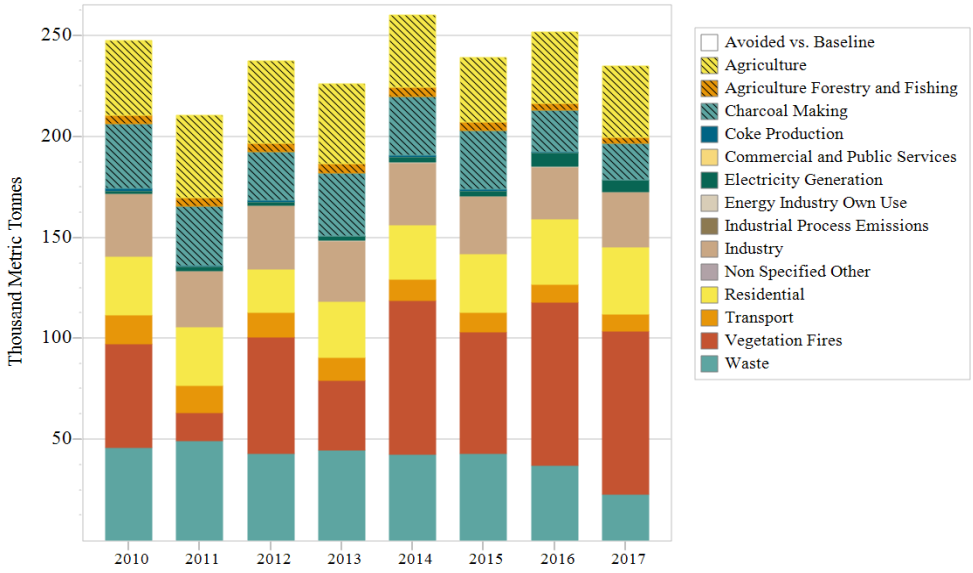



**Figure 5.3:** OC emission from different sources between 2010 and 2017

## 4) $NH_3$

Agricultural activities such as livestock enteric fermentation and manure management and fertilizer application were the biggest source of $NH_3$ emissions (86%), followed by industrial activity (7%), as shown in Figure 5.4 (see Appendix, Table S19).

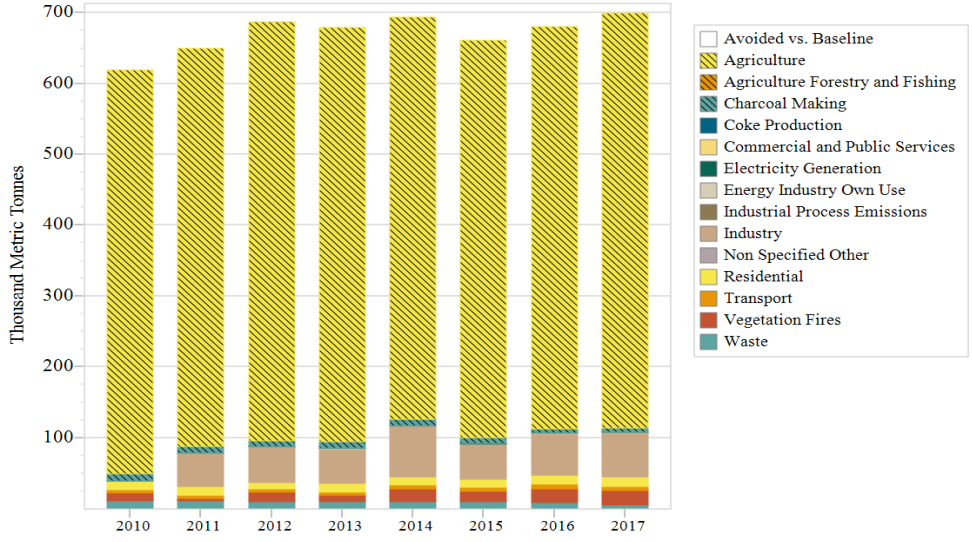



**Figure 5.4:** $NH_3$ emission from different sources between 2010 and 2017

## 5) $NO_X$

The combustion of fossil fuel in the transport sector (46%) was the biggest source of NOx emission, followed by electricity generation (13%), industry (12%), agriculture forestry and fishing (10%) etc. A trend of the emission from transport sector was steady as shown in Figure 5.5 (see Appendix, Table S20).

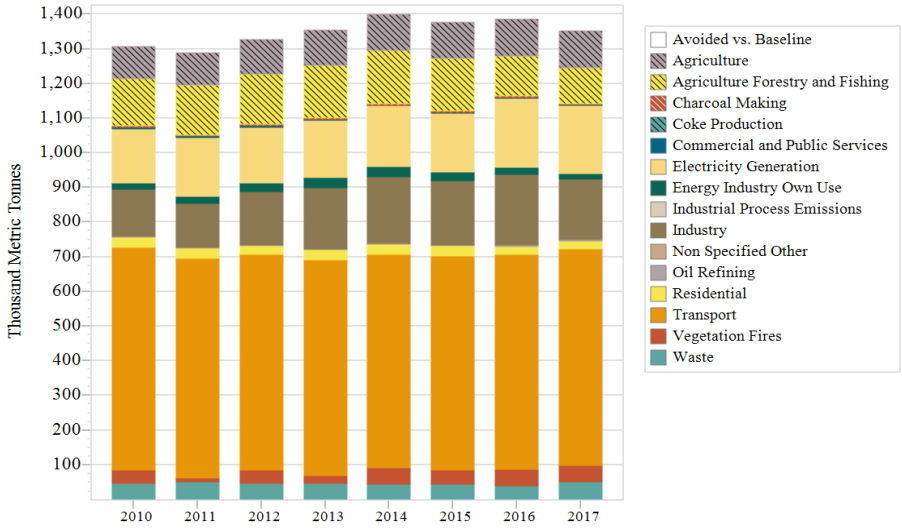



**Figure 5.5:** $NO_X$ emission from different sources between 2010 and 2017

## 6) $SO_2$

$SO_2$ emissions also play a significant role in $PM_{2.5}$ formation as a precursor. Electricity generation was the main source of $SO_2$ emissions (44%), followed by industry (40%), agriculture forestry and fishing (8%) and oil refining (5%), as shown in Figure 5.6 (see Appendix, Table S21).

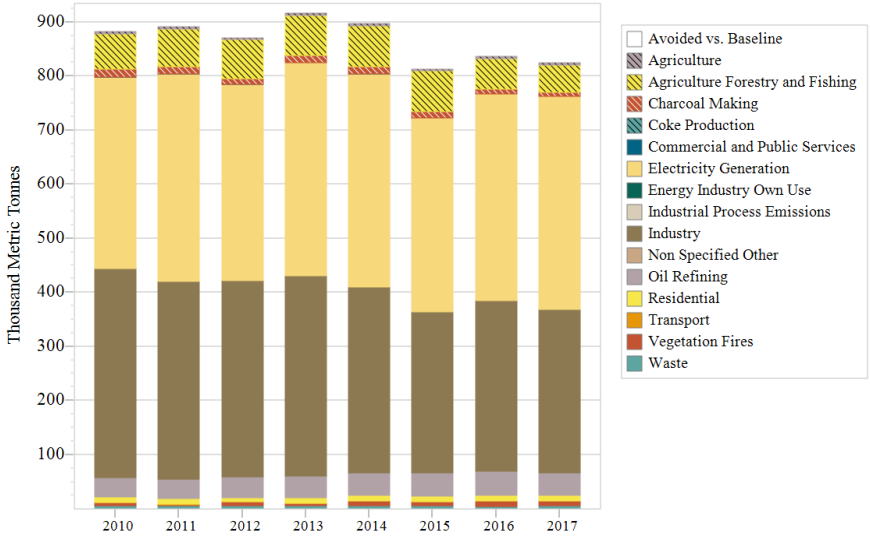



**Figure 5.6:** $SO_2$ emission from different sources between 2010 and 2017

In summary, there were various potential sources from different sectors that could emit $PM_{2.5}$, BC, OC, $NH_3$, $NO_x$ and $SO_2$ to the atmosphere. Therefore, to reduce the emissions in all relevant sectors, actions are needed across multiple pollutants emitted from a wide range of source sectors.

## 5.3.2 Baseline emissions

Baseline emissions were estimated for future years from 2018 to 2030 compared to the base year level in 2010 at national level.

A business as usual (BAU) scenario, to project the emissions of $PM_{2.5}$, BC, OC, $NH_3$, $NO_x$ and $SO_2$ from different sources from 2018 to 2030, was developed for each pollutant as described below.

### 1) $PM_{2.5}$

Under the baseline scenario, the total $PM_{2.5}$ emissions are expected to increase between 2018 and 2030 from 480 kt $yr^{-1}$ in 2018 up to 532 kt $yr^{-1}$ in 2030 (Figure 5.7). However, the changes of the total emissions during 2010 to 2017 fluctuated between 471 and 562 kt $yr^{-1}$. The main reason for this fluctuation was the variability in emissions from vegetation fires, which we projected into the future based on the 2010-2017 average annual average burned. The largest sources of $PM_{2.5}$ emission in the baseline scenario are vegetation fires expected to emit 18% in 2030, then follow by industry (17%), residential (14%), agriculture (13%), electricity generation (14%), waste (9%) and charcoal making (7%) sectors. The vegetation fires sector is categorized into on-site burning of forests and grassland, and savanna burning. Forests and grassland burning are expected to continue to make a large contribution to total emissions, but the increase in emissions expected between 2018 and 2030 are based on increases in activities in other sectors (as the annual area of forest and other vegetation burned was estimated to stay constant). The trends of the $PM_{2.5}$ emissions show that agriculture, charcoal making, electricity generation and industry sectors tend to increase by the largest proportion. In contrast, the residential and transport sectors tend to decrease slightly.

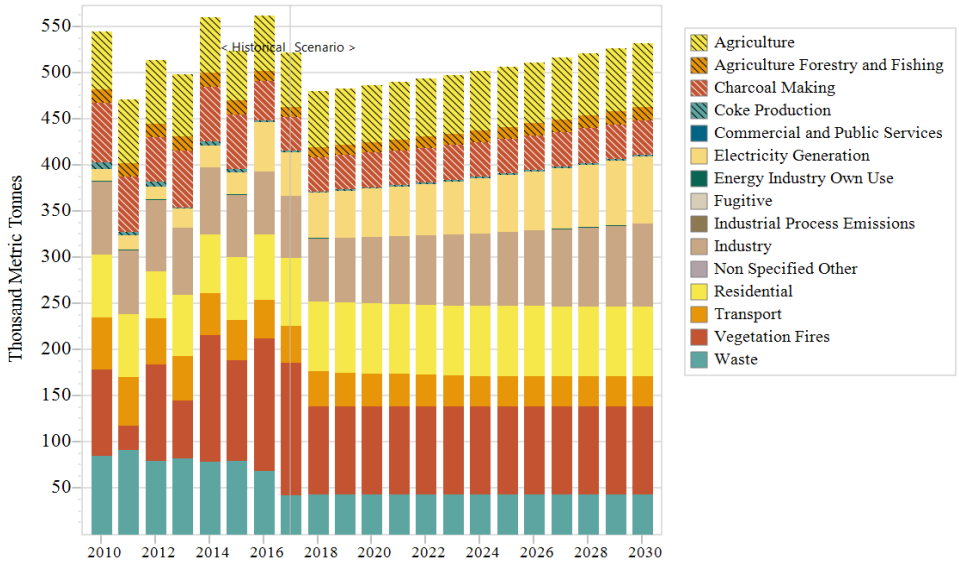



**Figure 5.7:** The estimation of $PM_{2.5}$ emissions from different sources under baseline scenario

## 2) BC

The baseline scenario of BC emissions shows the similar trends to $PM_{2.5}$ emissions, which are expected to increase until 2030. A range of total emissions between 2010 and 2017 were 80 -89 kt $yr^{-1}$. The transport sector is still expected to be the largest source with consistent increasing pattern during 2018 to 2030. In 2030, the transport sector is estimated to emit 29% of total BC emissions, mainly by road transport from pickup vehicles that use diesel. The industry sector is expected to be the second main source with 23% from gas diesel oil, then follow by residential sector (15%) by using traditional stove from wood, charcoal, and vegetal wastes as presented in Figure 5.8.

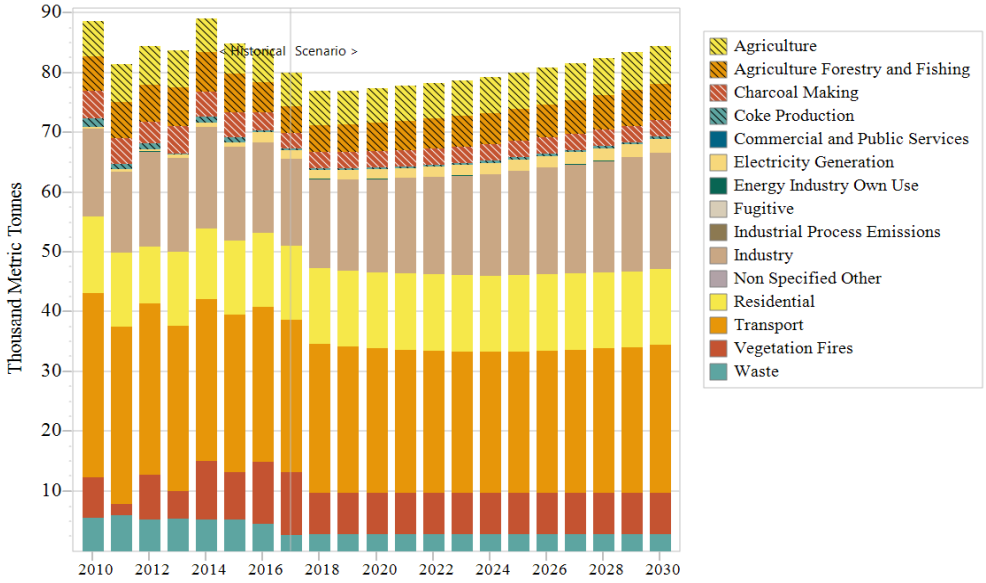



**Figure 5.8:** The estimation of BC emissions from different sources under baseline scenario

## 3) OC

The changes in OC emissions under the baseline scenario show that total OC emissions mainly come from on-site burning of forests and grassland, and agricultural residue burning as presented in Figure 5.9. The trends of the emissions in the baseline scenario in agriculture, agriculture forestry and fishing, charcoal making, electricity generation, industry, vegetation fires and waste sectors are estimated to increase steadily from 210 kt $yr^{-1}$ in 2018 to 225 kt $yr^{-1}$ in 2030. However, the emissions in residential and transport sectors tend to decrease. The average of OC emissions in 2030 are expected to emit 23% from forest burning in vegetation fires, agriculture (18%), industry (16%), residential (15%), waste (10%), and charcoal making (9%).

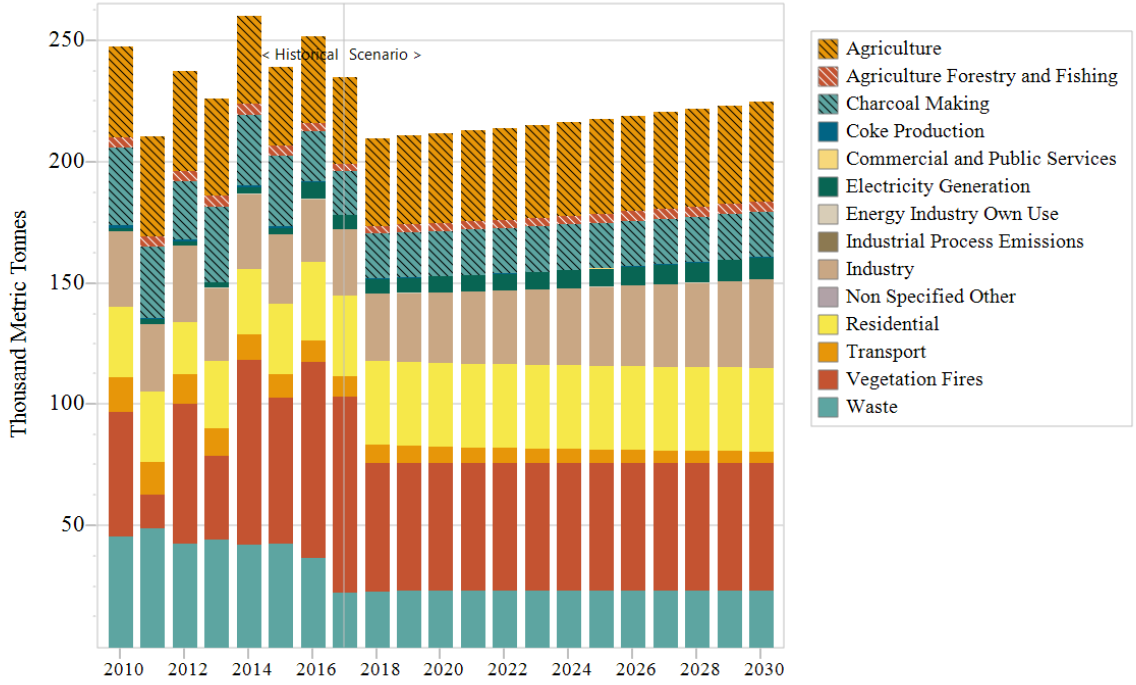



**Figure 5.9:** The estimation of OC emissions from different sources under baseline scenario

## 4) $NH_3$

The increasing of $NH_3$ emissions under the baseline scenario is shown in Figure 5.10. The total $NH_3$ emissions increase from 618 kt $yr^{-1}$ in 2010 to 813 kt $yr^{-1}$ in 2030. The total emissions are expected to increase about 31% in 2030 when compared with the base year 2010. The agriculture sector was the major source of the emissions in 2010 and still remains the major source in 2030. The baseline scenario projects that in 2030, 84% of the emissions in agriculture sector will come from livestock enteric fermentation and manure management (poultry, cattle, pig) and fertilizer application mainly from urea, industry

(10%) and from other sources such as residential, transport, vegetation fires sector and waste (6%).

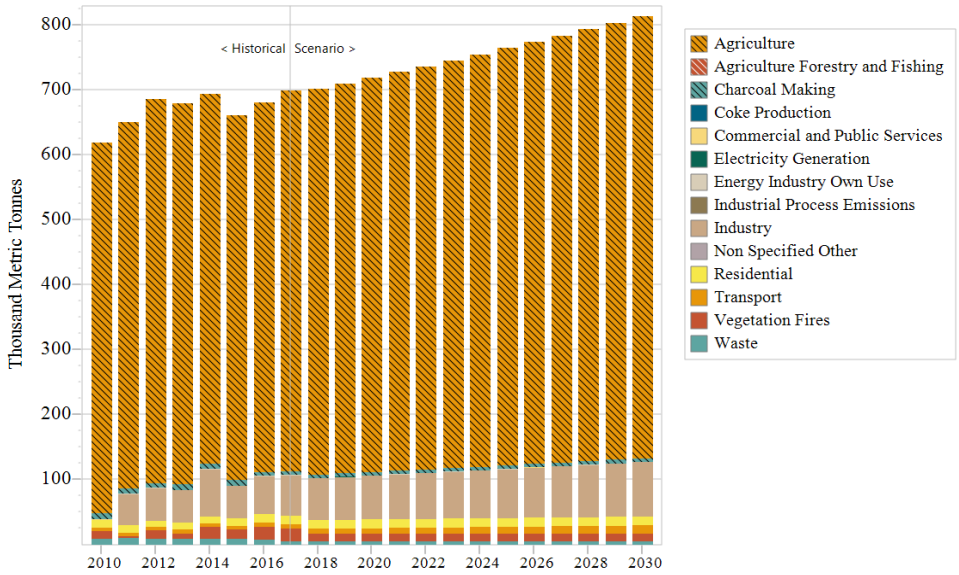



**Figure 5.10:** The estimation of $NH_3$ emissions from different sources under baseline scenario

## 5) $NO_X$

Overall, total $NO_X$ emissions are projected to increase steadily from 2010 to 2030 in each main source sector, transport sector was the biggest emission source of $NO_X$ emissions in 2010. The total emissions are expected to emit 47% and increase 35% in 2030 from 1,305 kt $yr^{-1}$ in the base year 2010 to 1761 kt $yr^{-1}$ in 2030. On-road vehicles such as truck, pickup bus, motorcycles, passenger cars etc. that mainly use diesel fuel are the major sources of the emissions. Electricity generation is the second source of the emissions that is projected to increase 17% by 2030 from fuels used to generate the electricity, for example, bituminous coal and anthracite, gas diesel oil, LPG, BKB brown coal briquettes and etc., then followed by the industry process of iron and steel (13%), agriculture forestry and fishing (8%), agriculture (7%), waste (3%), vegetation fires (2%) and others (3%), as shown in Figure 5.11.

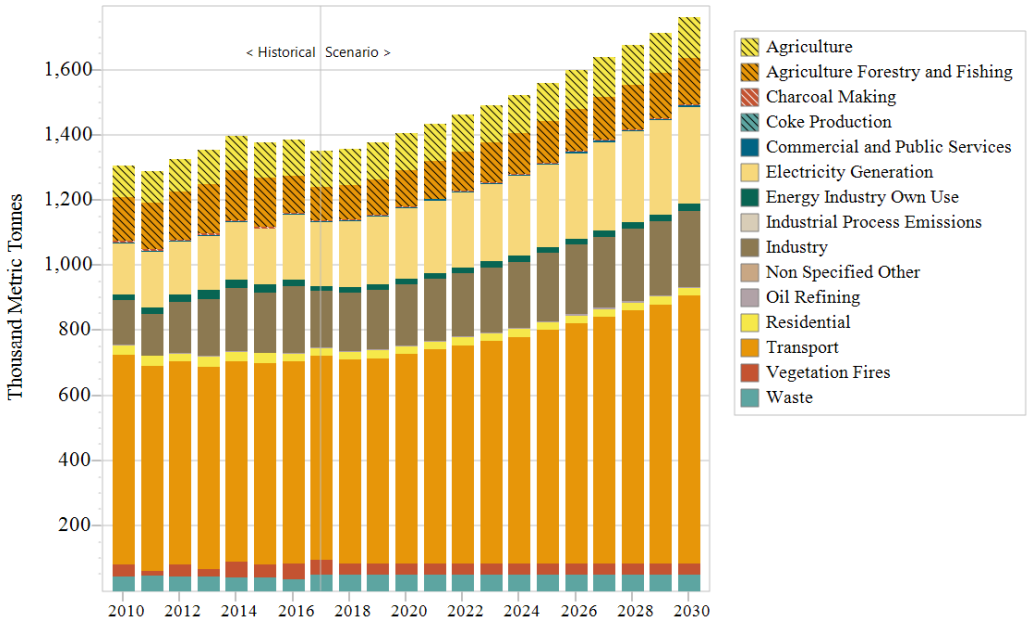



**Figure 5.11:** The estimation of $NO_x$ emissions from different sources under baseline scenario

## 6) $SO_2$

The total $SO_2$ emissions under the baseline scenario in base year 2010 was 881 kt $yr^{-1}$ and are projected to increase to 1,169 kt $yr^{-1}$ in 2030 (33%). Electricity generation is the main source of $SO_2$ emissions and is projected to increase 70% from 353 kt $yr^{-1}$ in the base year to 601 kt $yr^{-1}$ in 2030. The second emission source comes from the iron and steel production in industry sector, which is expected to increase only 4% in 2030. In agriculture forestry and fishing, the emissions are projected to increase by 6% in 2030. However, the trends of $SO_2$ emissions in oil refining, residential, transport, vegetation fires and waste sectors are projected to be stable as shown in Figure 5.12.

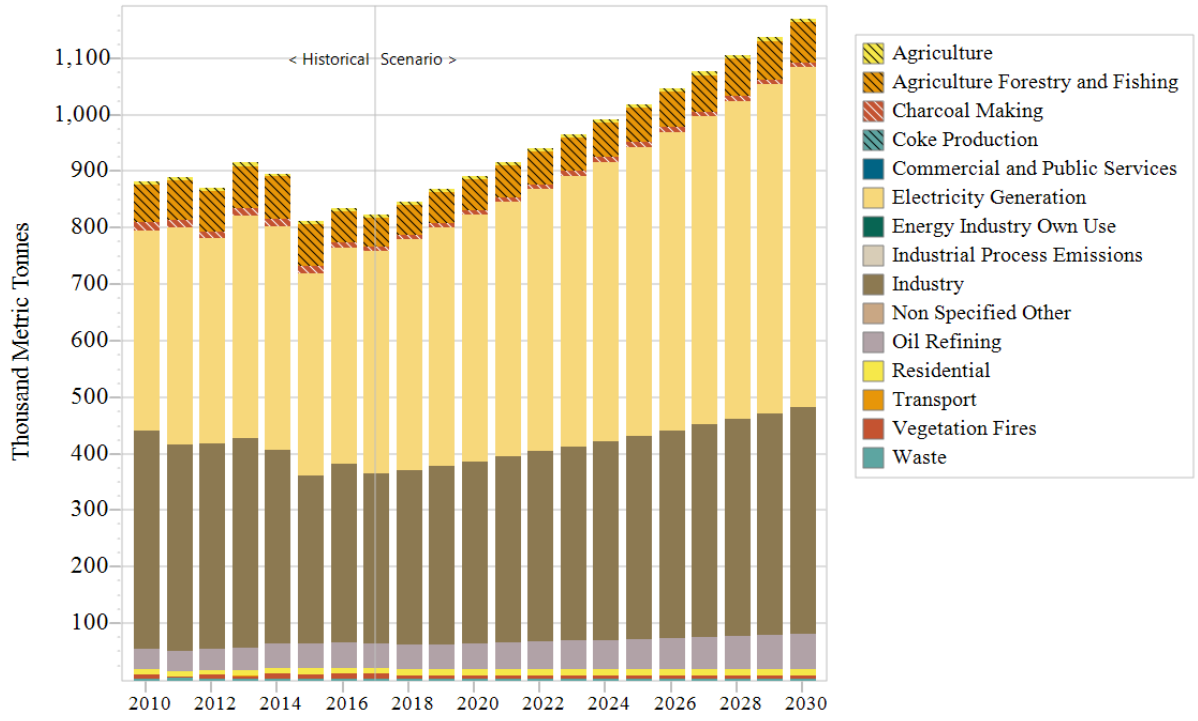



**Figure 5.12:** The estimation of $SO_2$ emissions from different sources under baseline scenario

A comparison of the results from this study to emission inventories from different studies in Thailand at national level in different base years are shown in Table 5.6. The emission trends of this study show the consistent values compared to previous studies from all sources. When comparing sector by sector in the crop residue burning and forest fires sectors, the emissions also show the similar trends. However, the differences between emissions of $NH_3$, $NO_x$ and $PM_{10}$ in this study and previous studies differ, predominantly because of the differences in the major sources of these pollutants, and differences in the data and assumptions to characterise each sector in different studies. For example, in this study, $PM_{10}$ emission comes from all sources 614.9 kt $yr^{-1}$ (mostly comes from vegetation fires and residential sector (Table 5.6 and Figure 5.1 ) but in Vongmahadlek, et al. (2009), the national total $PM_{10}$ emission were almost double this value. Both studies estimate the majority of $PM_{10}$ emissions to come from biomass burning, which were substantially different in the years of each inventory (2010 vs 2005). In contrast, the emissions of $NH_3$ were substantially similar, because these emissions were mainly from livestock and fertiliser application. Livestock numbers of tonnes of fertiliser applied were similar in this study and Vongmahadlek, et al. (2009). However, the large increase in number of vehicles between 2010 and 2005 results in substantially higher NOx emissions in this study compared to Vongmahadlek, et al. (2009)

**Table 5.6:** Comparison of emission inventories from different studies in different base years across Thailand (kt $yr^{-1}$)

| **Pollutants** | **Thailand** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **This study** | **Vongmahadlek *et al.* (2009)** | **This study** | **Kim Oanh et al. (2018)** | **Kanabkaew and Kim Oanh (2011)** | **This study** | **Kim Oanh et al. (2018)** |
| | **2010** | **2005** | **2010** | **2010** | **2007** | **2010** | **2010** |
| $PM_{2.5}$ | 544.7 | - | 62.3 | 84 | 128 | 93.3 | 80 |
| $PM_{10}$ | 614.9 | 1277.4 | 65.7 | 90 | 143 | 119.3 | 100 |
| BC | 88.6 | 136.4 | 5.7 | 7.2 | - | 6.8 | 5 |
| OC | 247.6 | 325.5 | 37.4 | 31 | 54 | 51.1 | 40 |
| $NH_3$ | 618.5 | 439.2 | 27.2 | 38 | 59 | 11.9 | 24 |
| $NO_x$ | 1304.8 | 790.3 | 26.9 | 29 | 42 | 37.1 | 22 |
| $SO_2$ | 881.1 | 886 | 3.6 | 3 | 4 | 6.1 | 6 |
| **Source** | **All sources** | | **Crop residue burning** | | | **Forest fires** | |

In summary, under baseline scenarios based on existing activities, emissions of all PM and PM precursor emissions are projected to increase by 20-40% between 2018 and 2030. The most important source sectors are vegetation fires for $PM_{2.5}$ and OC emissions, transport for BC and $NO_x$ emissions, agriculture for $NH_3$ emissions, and electricity generation for $SO_2$ emissions. The pollutants with the highest increase in emissions between 2018 and 2030), i.e. $SO_2$ and $NO_x$ result from their emission deriving mainly from energy sector sources. The baseline projection estimates that there will be a 3.9% per year increase in GDP in Thailand, as well as increase in population from 67 million in 2010 to 70 million in 2030. Both of these trends are associated with increases in energy consumption (and therefore production), which, in the absence of the implementation of mitigation measures, will result in additional fuel consumption and associated emissions. Other pollutants, such as BC, OC, and $PM_{2.5}$ also increase predominantly as a result of increases in energy consumption and production.

The other major source sectors, such as vegetation fires, are not projected to increase substantially, in line with historical trends show little change over time, and due to a lack of information on the likely effect of other drivers (e.g. climate change) on the distribution, severity and frequency of vegetation fires.

Therefore, the potential to reduce the emissions of these pollutants in all source sectors need to implement existing and additional mitigation measures in order to achieve the low emissions as described in the section below.

### 5.3.3 Mitigation scenarios

The estimation of emissions under current activities from previous section are likely to increase in the future in the baseline scenario. Therefore, in order to mitigate the emissions from different sources, existing policies and additional mitigation measures were modelled. These focussed on the major emission sources in 2030 by considering mitigation measures in seven source sectors, i.e. transport, residential, industry, agriculture, vegetation fires, waste and electricity generation sectors with 11 measures as presented in Table 5.4. Two mitigation scenarios were evaluated, one which considered the full implementation of measure included in existing plans and strategies, and a scenario which considered the implementation of additional mitigation measures designed to reduce emissions further. The estimation of total emissions from key sectors for baseline scenarios, existing and additional measures across Thailand in 2030 are presented in Table 5.7.

When compared to baseline scenarios (Avoided vs. Baseline), the results showed that the total emissions of $PM_{2.5}$, BC, OC, $NH_3$, $NO_X$, and $SO_2$ with implementation of existing measures are expected to reduce in 2030 by 33%, 25%, 37%, 5%, 12% and 17%, respectively. In contrast, when both existing and additional measures this could reduce more emissions of $PM_{2.5}$, BC, OC, $NH_3$, $NO_X$, and $SO_2$ by 70%, 58%, 78%, 32%, 23% and 28%, respectively. The reductions for each pollutant are described in the sub-section below.

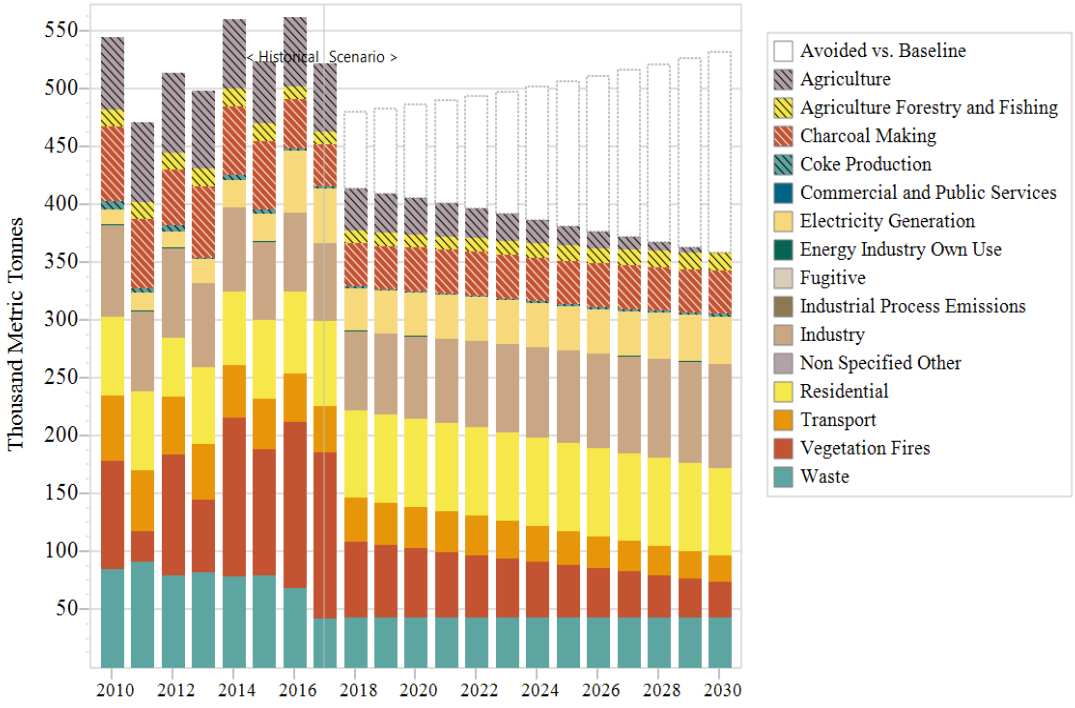
**Table 5.7:** Total emission inventories and key sector emissions for baseline, existing and additional scenarios in Thailand 2030 (kt $yr^{-1}$)

| Sectors | Emissions (kt $y^{-1}$) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $PM_{2.5}$ | | | BC | | | OC | | | $NH_3$ | | | $NO_X$ | | | $SO_2$ | | |
| | Baseline Scenarios | Existing measures | Additional measures | Baseline Scenario | Existing measures | Additional measures | Baseline Scenario | Existing measures | Additional measures | Baseline Scenario | Existing measures | Additional measures | Baseline Scenario | Existing measures | Additional measures | Baseline Scenario | Existing measures | Additional measures |
| Agriculture forestry and fishing | 14.7 | 14.7 | 14.7 | 6.1 | 6.1 | 6.1 | 4.3 | 4.3 | 4.3 | - | - | - | 143.7 | 143.7 | 143.7 | 70.4 | 70.4 | 70.4 |
| Commercial and public services | 0.1 | - | - | - | - | - | - | - | - | 0.1 | 0.1 | 0.1 | 4.5 | 3.6 | 3.6 | - | - | - |
| Energy industry own use | 0.3 | 0.3 | 0.3 | - | - | - | 0.2 | 0.2 | 0.2 | 0.5 | 0.5 | 0.5 | 21.0 | 21.0 | 21.0 | - | - | - |
| Industry | 89.5 | 89.5 | 50.1 | 19.5 | 19.5 | 11.3 | 36.2 | 36.2 | 18.9 | 83.9 | 83.9 | 84.4 | 233.4 | 233.4 | 217.8 | 401.5 | 401.5 | 295.4 |
| Residential | 76.0 | 76.0 | 0.7 | 12.8 | 12.8 | - | 34.5 | 34.5 | 0.1 | 13.6 | 13.6 | - | 23.6 | 23.6 | 2.0 | 10.6 | 10.6 | - |
| Transport | 32.8 | 22.6 | 20.6 | 24.7 | 15.5 | 14.2 | 4.7 | 4.0 | 3.7 | 12.3 | 9.3 | 9.2 | 822.6 | 778.3 | 645.7 | 0.2 | 0.2 | 0.2 |
| Agriculture | 68.0 | - | - | 6.3 | - | - | 40.8 | - | - | 679.4 | 649.7 | 453.3 | 120.8 | 91.6 | 91.6 | 4.1 | - | - |
| Vegetation fires | 95.2 | 30.8 | 30.8 | 6.9 | 2.3 | 2.3 | 52.8 | 16.0 | 16.0 | 12.6 | 3.4 | 3.4 | 34.2 | 16.9 | 16.9 | 6.2 | 2.1 | 2.1 |
| Waste | 43.8 | 43.8 | 0.1 | 2.9 | 2.9 | - | 23.5 | 23.5 | - | 5.0 | 5.0 | - | 51.2 | 51.2 | 29.4 | 3.8 | 3.8 | 1.6 |
| Charcoal making | 37.6 | 37.6 | - | 2.8 | 2.8 | - | 18.7 | 18.7 | - | 5.4 | 5.4 | - | 2.6 | 2.6 | - | 8.3 | 8.3 | - |
| Coke production | 2.0 | 2.0 | 2.0 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 | - | - | - | - | - | - | - | - | - |
| Electricity generation | 72.3 | 41.1 | 41.1 | 2.2 | 1.3 | 1.3 | 8.8 | 5.1 | 5.1 | 0.1 | 0.1 | 0.1 | 298.8 | 184.1 | 184.1 | 601.5 | 406.9 | 406.9 |
| Oil refining | - | - | - | - | - | - | - | - | - | - | - | - | 4.1 | 4.1 | 4.1 | 62.5 | 62.2 | 63.2 |
| **Total emission** | **532.1** | **358.3** | **160.3** | **84.5** | **63.4** | **35.6** | **224.8** | **142.7** | **48.7** | **812.8** | **770.9** | **550.9** | **1760.5** | **1554.1** | **1359.9** | **1168.9** | **966.0** | **839.7** |
| **Avoided vs. Baseline** | **-** | **173.9** | **371.8** | **-** | **21.1** | **48.9** | **-** | **82.0** | **176.1** | **-** | **41.9** | **262.0** | **-** | **206.5** | **400.6** | **-** | **203.0** | **329.2** |
| **Reduction (%)** | **-** | **32.7** | **69.9** | **-** | **24.9** | **57.9** | **-** | **36.5** | **78.4** | **-** | **5.2** | **32.2** | **-** | **11.7** | **22.8** | **-** | **17.4** | **28.2** |

## 1) $PM_{2.5}$

Based on the baseline emissions from previous section, vegetation fires are predicted to be the biggest source of $PM_{2.5}$. Therefore, mitigation measures as presented in Table 5.3 were implemented. Figure 5.13 shows the emissions after implementing existing measures (Figure 5.13a) and additional measures (Figure 5.13b). In 2030, the implementation of existing measures could reduce $PM_{2.5}$ emissions by 33% (173.9 kt $yr^{-1}$) from all source sectors compared to the baseline scenario, while the implementation of additional measures could reduce more emissions by 70% (371.8 kt $yr^{-1}$) from all source sectors as shown in Table 5.7. In addition, the implementation of additional measures by sectors could reduce emissions from vegetation fires 68%, waste 100%, residential 99%, industry 44%, electricity generation 43%, transport 37%, and etc.

(a) Existing measures



(b) Additional measures

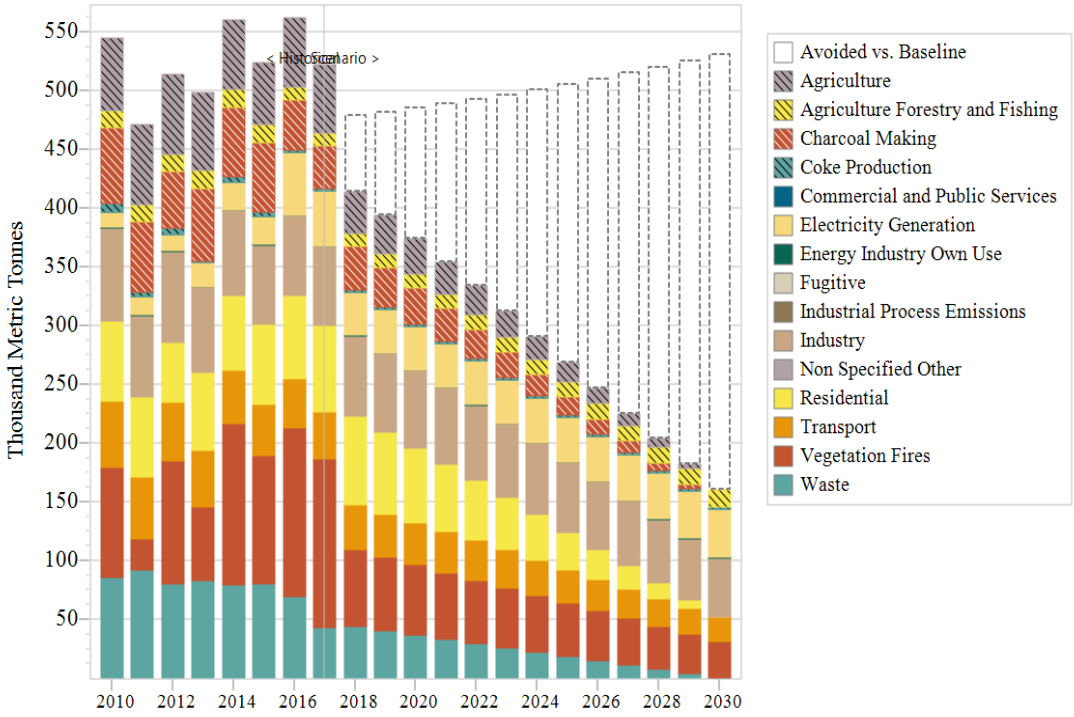
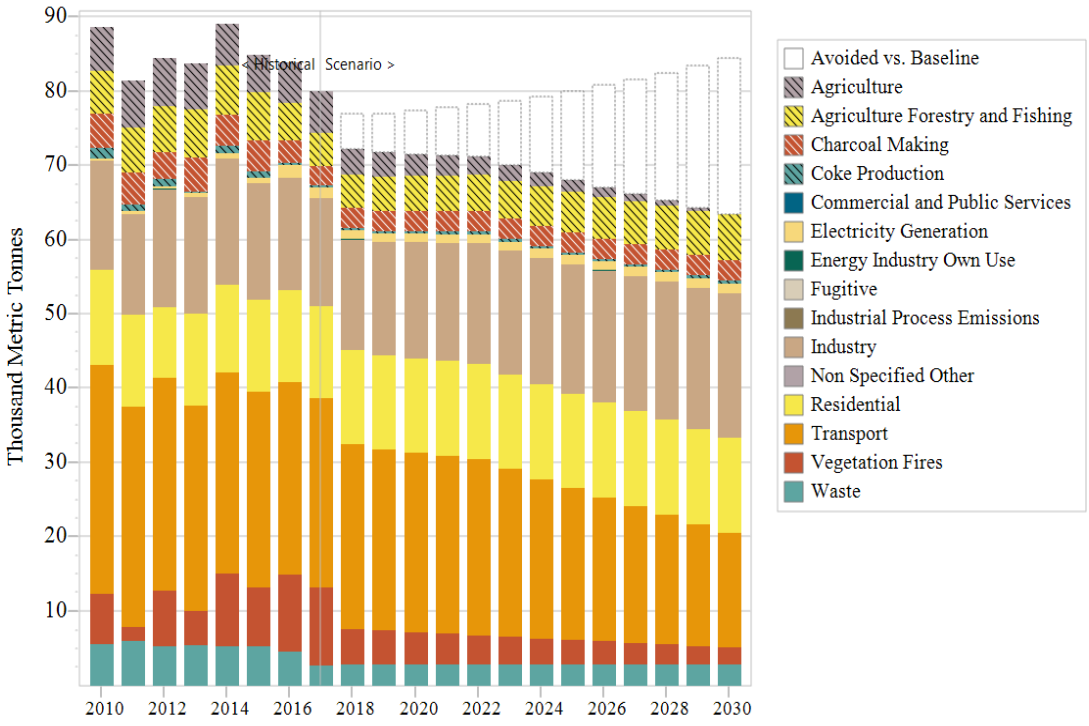



**Figure 5.13:** $PM_{2.5}$ emissions reduction from (a) Existing measures and (b) Additional measures

## 2) BC

The main sources of BC emissions are transport, industry, and residential sectors. However, transport sector is expected to be the biggest source of BC emission. Figure 5.14 shows the emissions after implementing existing measures (Figure 5.14a) and additional measures (Figure 5.14b). In 2030, the implementation of existing measures could reduce BC emissions by 25% (21.1 kt $yr^{-1}$) from all source sectors compared to the baseline scenario, while the implementation of additional measures could reduce more emissions by 58% (49 kt $yr^{-1}$) from all source sectors as shown in Table 5.7. Moreover, the implementation of additional measures by sectors could reduce emissions from residential and waste sectors by 100%, vegetation fires 68%, industry, transport and electricity generation approximately 43%.

(a) Existing measures




(b) Additional measures

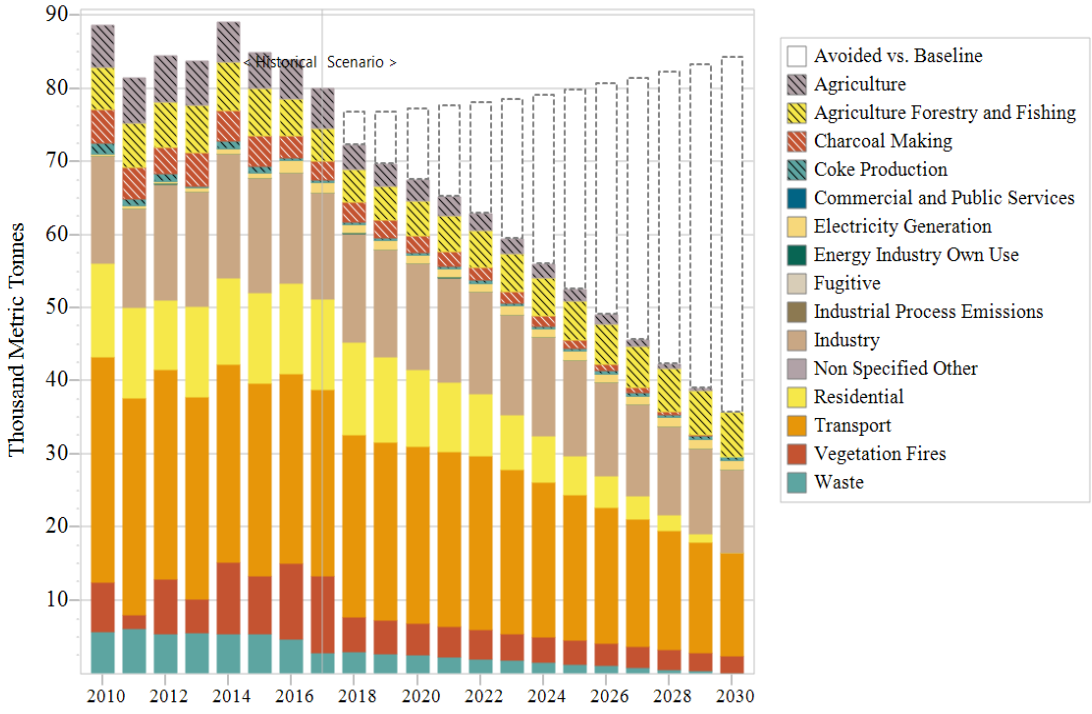
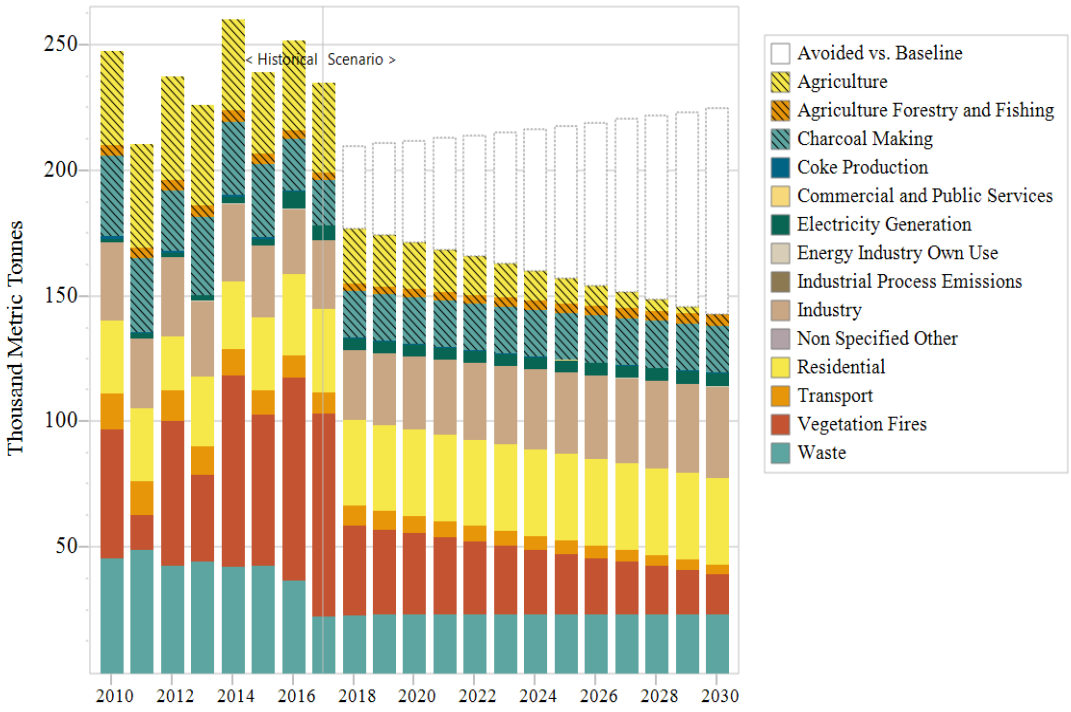



**Figure 5.14:** BC emissions reduction from (a) Existing measures and (b) Additional measures

## 3) OC

OC emissions are expected to increase mainly from biomass burning in vegetation fires and agriculture sectors. Figure 5.15 shows the emissions after implementing existing measures (Figure 5.15a) and additional measures (Figure 5.15b). In 2030, the implementation of existing measures could reduce OC emissions by 36.5% (82.0 kt $yr^{-1}$) from all source sectors compared to the baseline scenario, while the implementation of additional measures could reduce more emissions by 78.4% (176.1 kt $yr^{-1}$) from all source sectors as shown in Table 5.7. The implementation of additional measures by sectors could reduce emissions from residential sector by 99.6%, follows by vegetation fires 70%, industry 48%, transport 21%, electricity generation 42% and zero % from open waste burning.

(a) Existing measures



(b) Additional measures

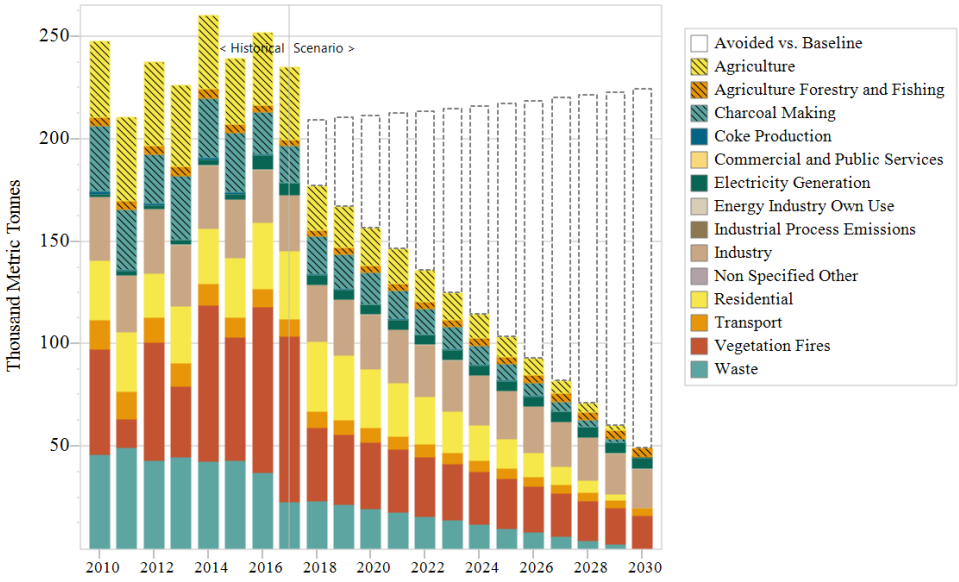
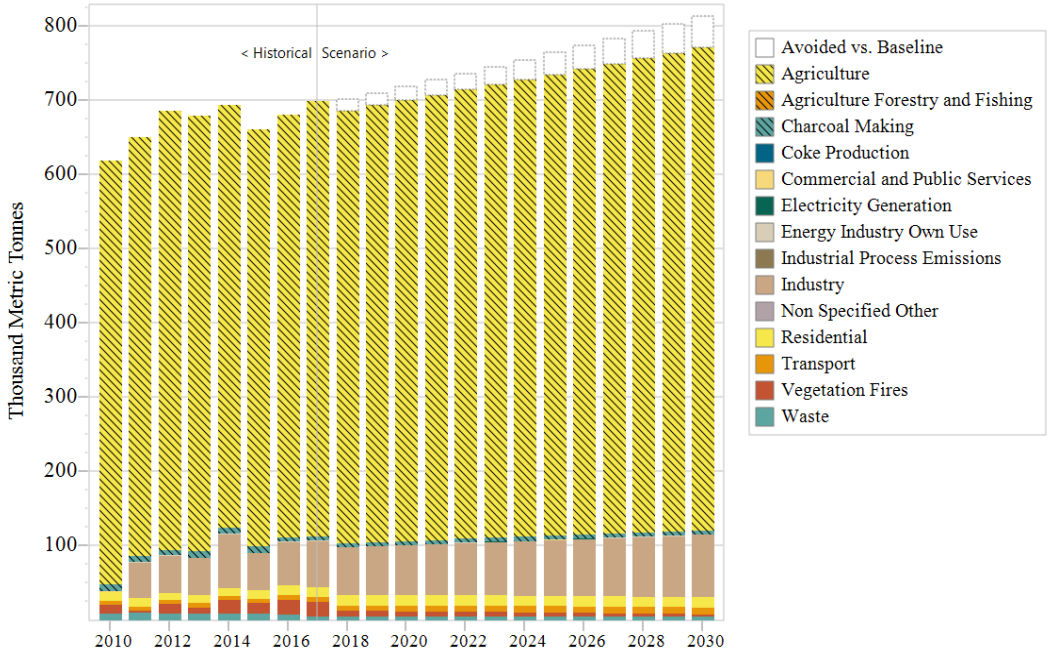



**Figure 5.15:** OC emissions reduction from (a) Existing measures and (b) Additional measures

## 4) $NH_3$

Agricultural fertilizer application is the biggest source of $NH_3$ emissions. Figure 5.16 shows the emissions after implementing existing measures (Figure 5.16a) and additional measures (Figure 5.16b). In 2030, the implementation of existing measures could reduce $NH_3$ emissions by 5% (41.9 kt $yr^{-1}$) compared to the baseline scenario, while the implementation of additional measures could reduce $NH_3$ emissions by 32% (262 kt $y^{-1}$) from all source sectors as shown in Table 5.7. In addition, the implementation of additional measures by sectors could reduce $NH_3$ emissions from agricultural sector by 33%, but in existing measures could reduce only 4%. For other sectors, there is not much difference for the changes of emissions. Table 5.7.

(a) Existing measures




(b) Additional measures

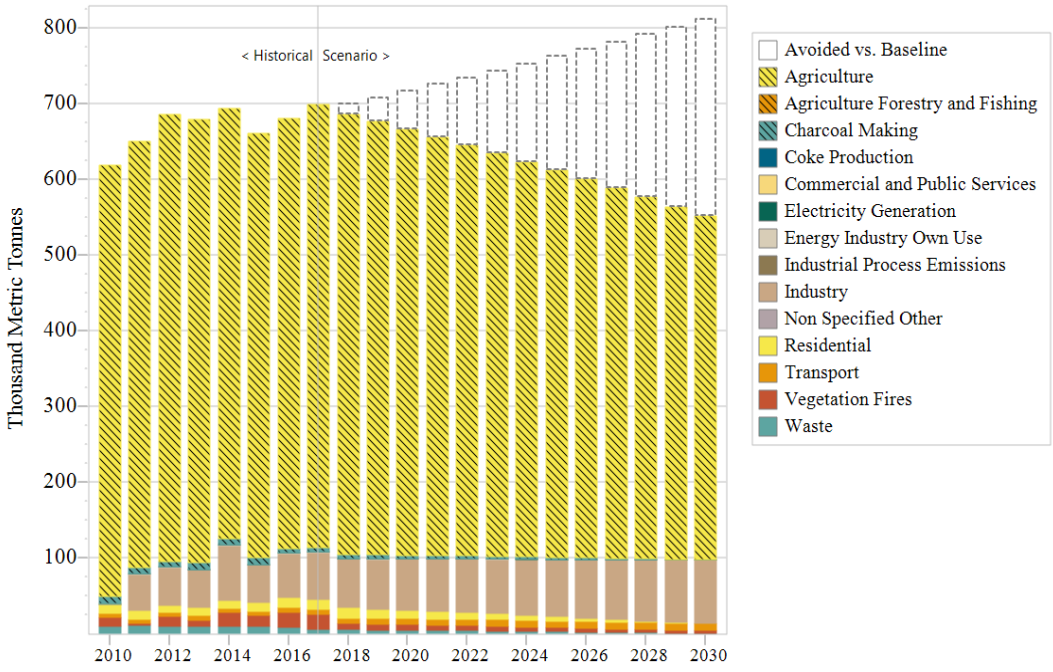
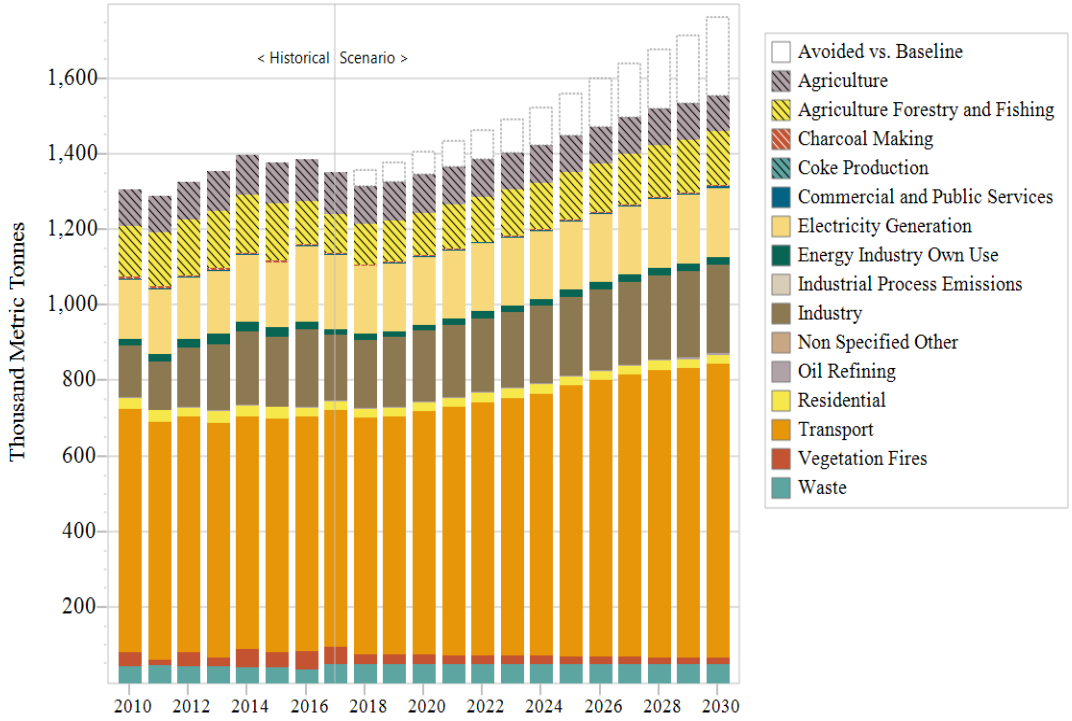



**Figure 5.16:** $NH_3$ emissions reduction from (a) Existing measures and (b) Additional measures

## 5) $NO_X$

The transport sector is predicted to be the biggest emission source of $NO_X$ emissions by 2030. Figure 5.17 shows the emissions after implementing existing measures (Figure 5.17a) and additional measures (Figure 5.17b). In 2030, the implementation of existing measures could reduce $NO_X$ emissions by 22% (206.5 kt $yr^{-1}$) from all source sectors compared to the baseline scenario, while the implementation of additional measures could reduce emissions by 23% (400.6 kt $yr^{-1}$) from all source sectors as shown in Table 5.7. In addition, the implementation of additional measures by sectors could reduce $NO_x$ emissions towards the end of the period in 2030 from main sectors such as transport sector is expected to reduce 22%, residential 92%, vegetation fires 51%, waste 43%, electricity generation 38%, agriculture 24%, and others.

(a) Existing measures



(b) Additional measures

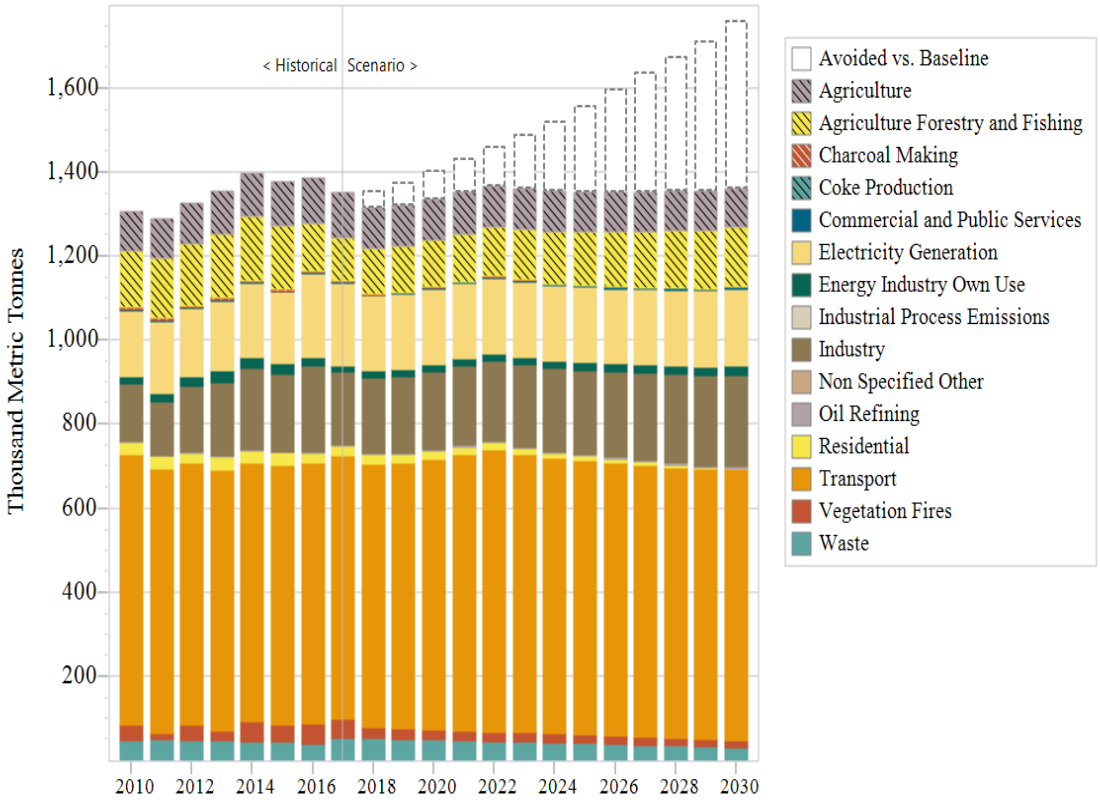



**Figure 5.17:** $NO_X$ emissions reduction from (a) Existing measures and (b) Additional measures

## 6) $SO_2$

The industry and electricity generation sectors are the major sources of $SO_2$ emissions. The projection of the emissions under the mitigation scenarios after implementing existing measures (Figure 5.18a) and additional measures (Figure 5.18b) shows that in 2030, could reduce $SO_2$ emissions from all source sectors by 17% (203 kt $yr^{-1}$) and by 28% (329.2 kt $yr^{-1}$), respectively as shown in Table 5.7. The reduction of emissions by source sectors from additional measures could reduce $SO_2$ emissions from electricity generation 32%, vegetation fires 65%, waste 58% and industry 26%.

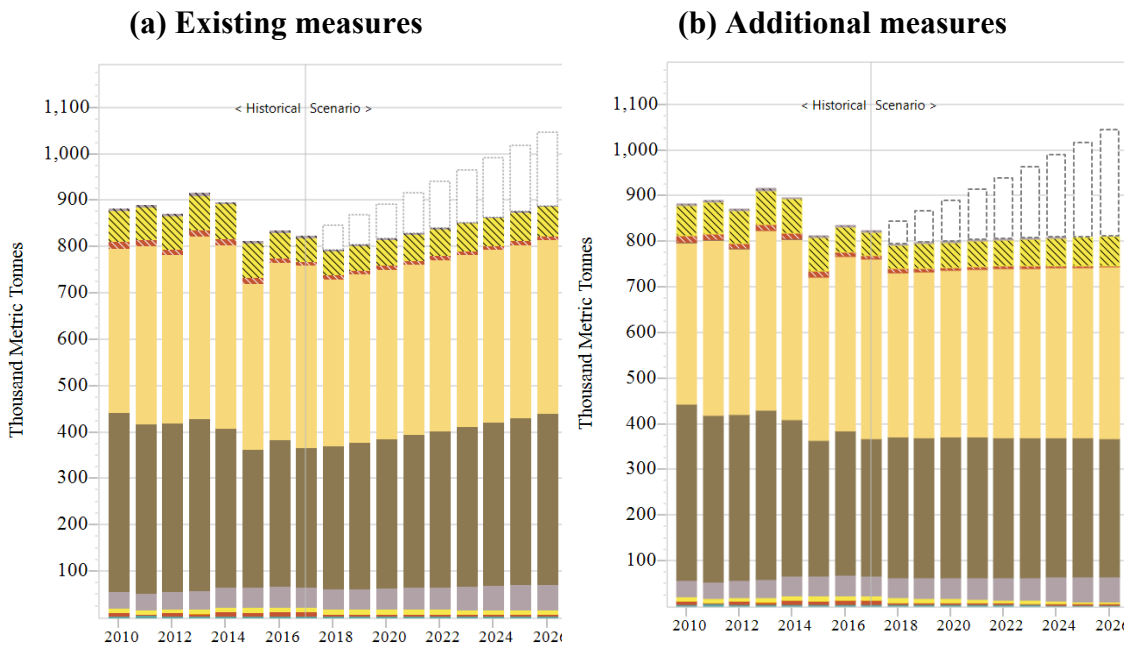



**Figure 5.18:** $SO_2$ emissions reduction from (a) Existing measures and (b) Additional measures

## 5.3.4 $PM_{2.5}$ concentration and health impacts

Emissions of primary $PM_{2.5}$, emissions as well as $PM_{2.5}$ precursors were converted into estimates of annual average population-weighted $PM_{2.5}$ concentrations across Thailand for each year and for each scenario using the LEAP-IBC tool (see Chapter 2 for details). Human exposure to $PM_{2.5}$ is related to health impacts, and therefore a health impact assessment was used to estimate the implications for human health from a particular level of $PM_{2.5}$ exposure estimated for each emission scenario. Figure 5.19 shows annual average population-weighted $PM_{2.5}$ concentrations across Thailand, split by the contribution of emissions of $PM_{2.5}$ precursor (BC, OC, $NH_3$, $NO_X$ and $SO_2$) estimated for 2010-2030 across Thailand. In 2010, the contribution to population-weighted annual $PM_{2.5}$ concentrations from national emission sources was estimated to be 48%, from anthropogenic emission outside of Thailand was 35% with the remainder from natural background (Figure 5.19). The contribution of $PM_{2.5}$ precursors to $PM_{2.5}$ concentration levels showed that $NH_3$ and $NO_x$ emissions made the largest contribution to annual population-weighted $PM_{2.5}$, 5.7 µg $m^{-3}$ and 4.6 µg $m^{-3}$, respectively in 2010, followed by OC (2.5 µg $m^{-3}$), $SO_2$ (0.9 µg $m^{-3}$), and BC (0.6 µg $m^{-3}$) (Figure 5.19). Implementing the existing mitigation measures only was estimated to reduce annual $PM_{2.5}$ concentrations across Thailand by 7% (2.4 µg $m^{-3}$) in 2030 compared to the baseline scenarios in 2010

(Figure 5.19). Hence while the implementation of existing measures avoids future degradation of air quality compared to the baseline scenario, it does not improve air quality compared to current levels across Thailand. Therefore, to improve air quality, additional mitigation measures are needed. Figure 5.20 shows that the implementation of the additional mitigation measures considered in this study would reduce population-weighted $PM_{2.5}$ concentrations across Thailand by 23% (i.e. reduce 7.5 μg $m^{-3}$) in 2030 compared to the baseline scenario.

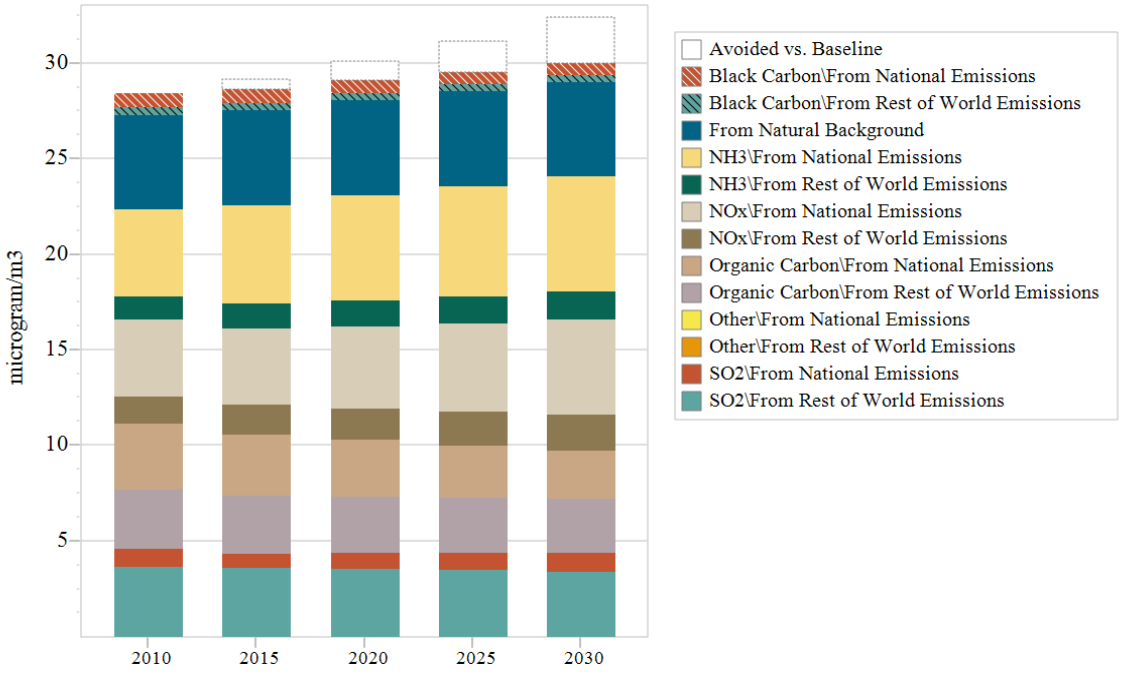



**Figure 5.19:** Annual average population-weighted $PM_{2.5}$ concentration across Thailand with contribution from natural background, national emissions and the rest of world emissions showing changes between 2010 and 2030 from implementation of existing measures

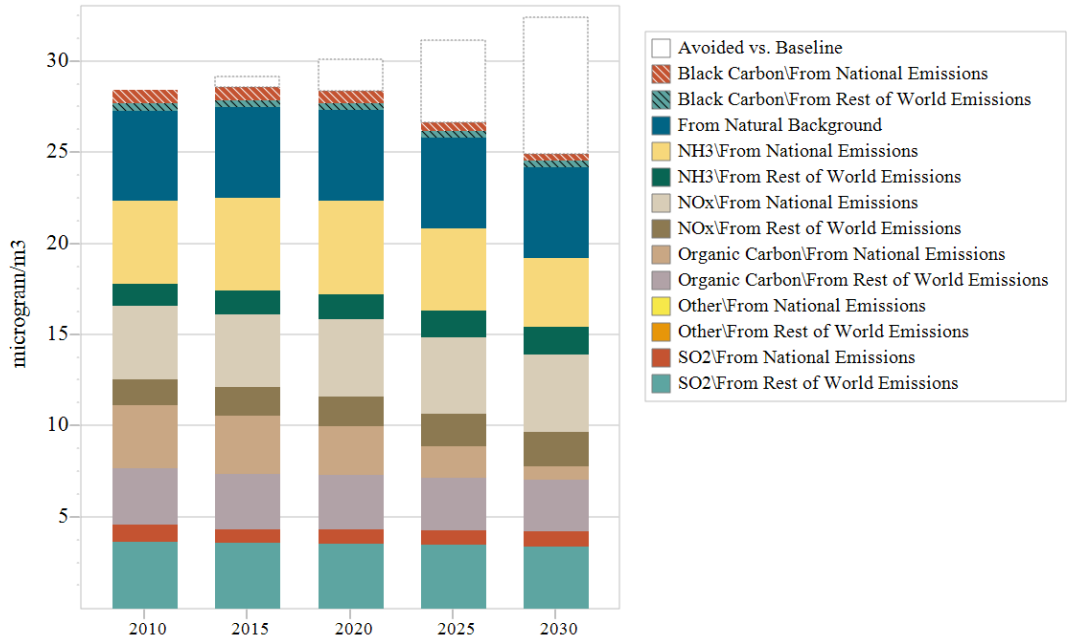



**Figure 5.20:** Annual average population-weighted $PM_{2.5}$ concentration across Thailand with contribution from natural background, national emissions and the rest of world emissions showing changes between 2010 and 2030 from implementation of additional measures

The comparison of $PM_{2.5}$ concentration reduction when all scenarios were implemented are presented in Figure 5.21. $PM_{2.5}$ concentrations from additional measures compared to the baseline scenarios in 2010 is expected to reduce 12% (reduce 3.5 μg $m^{-3}$) in 2030. However, $PM_{2.5}$ concentrations in existing measures and baseline scenarios are expected to increase.

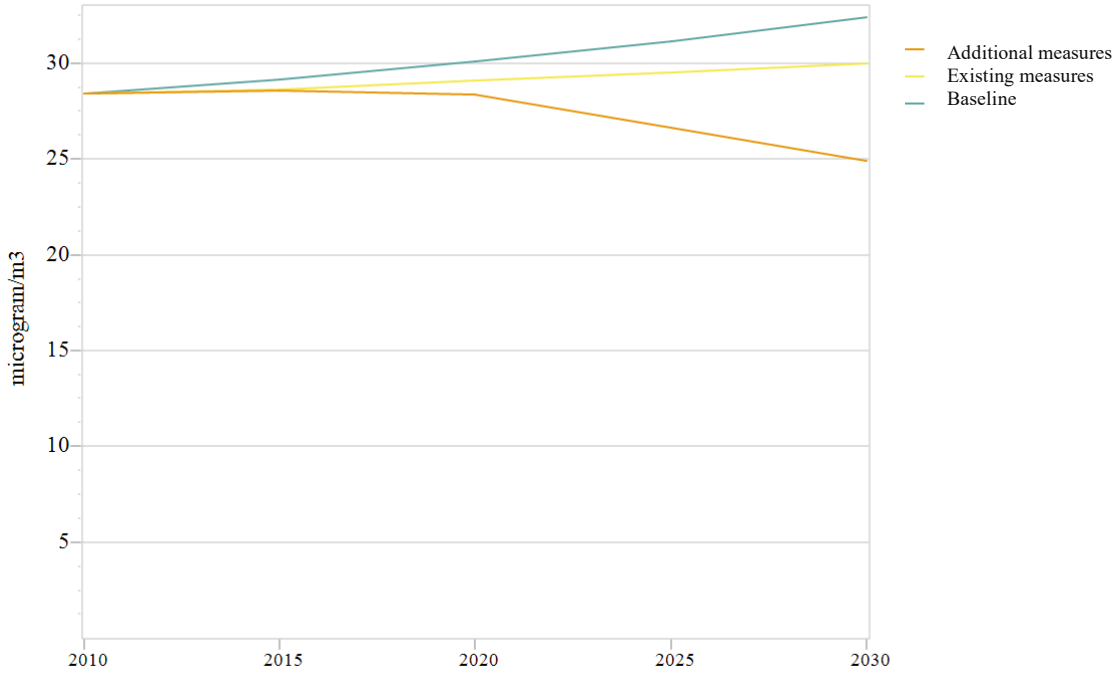



**Figure 5.21:** Comparison of $PM_{2.5}$ concentrations from different scenarios

In Thailand, the population is at risk of exposure to $PM_{2.5}$ concentration exceeding WHO air quality guideline (10 µg $m^{-3}$). The health impact assessment for this study was focused on the premature deaths and the population being exposed to $PM_{2.5}$ between 2010 and 2030. Figure 5.22 shows the estimation of premature deaths from $PM_{2.5}$ with different diseases. In the baseline scenario, in 2010, the number of premature deaths from acute lower respiratory infections (ALRI), chronic obstructive pulmonary disease (COPD), ischaemic heart disease lung cancer and stroke were 22,378 people and expected to increase to 39,113 people in 2030. This increase in premature deaths is a combination of increasing population-weighted $PM_{2.5}$ concentrations across Thailand, but also a larger and older population in 2030 compared to 2010, that is more susceptible to health impacts from air pollution exposure. The number of people aged less than 5 years and between 30 and 50 years were projected to decrease in 2030 by 47% and 35%, respectively. However, the population age 50 to 70 years and over 70 years are expected to increase 29% and 120%, respectively. Therefore, due to an aging population that are sensitive to $PM_{2.5}$ exposure, additional measures need to apply. The implementation of both the existing and additional mitigation measures was estimated to reduce the air pollution health burden in 2030 by 7,300 people premature deaths from air pollution in 2030 (19% reduction) as shown in Figure 5.22.

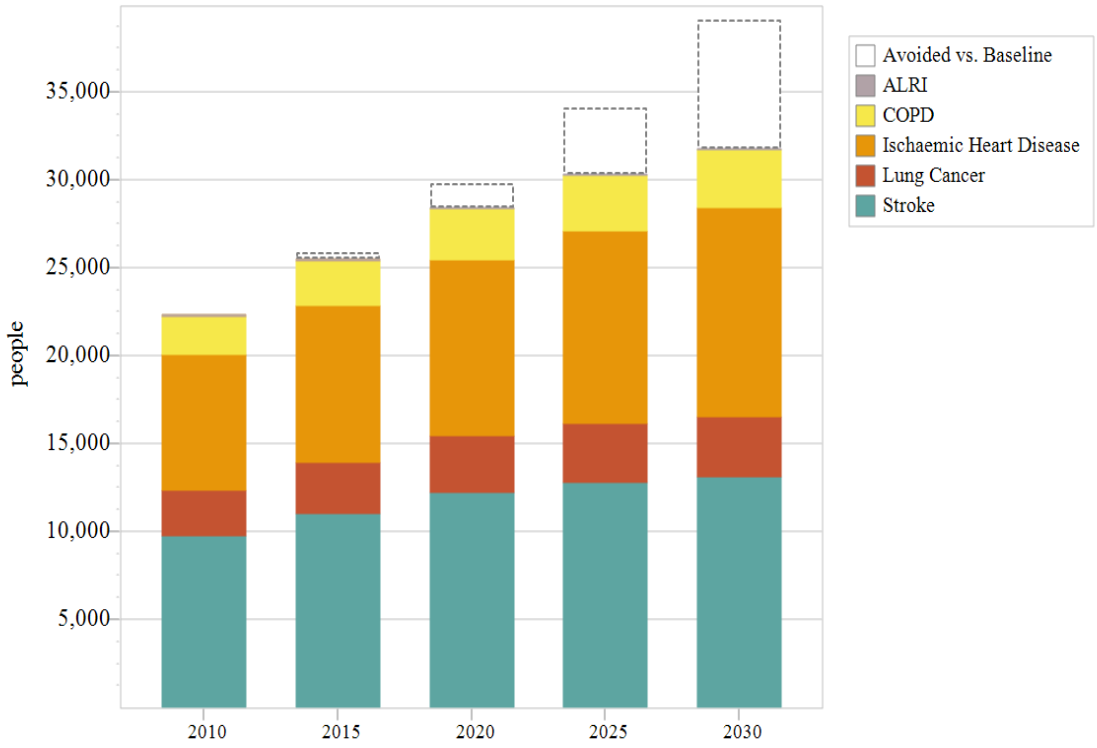



**Figure 5.22:** The number of people avoided premature mortality with additional measures

## 5.4 Discussion

In this study the LEAP-IBC tool was applied to develop the emission inventory of $PM_{2.5}$ and its precursors for Thailand between 2010 and 2030 at the national scale and to investigate the importance of different source sectors in determining air pollution concentrations and health effects. The study then considered the potential of existing and additional mitigation measures to reduce emissions by 2030. The findings from this study show that $PM_{2.5}$ and its precursors emissions are expected to increase by 2030 without any implementation of mitigation measure (Baseline scenario) due to continued population and economic growth as shown in Table 5.8. Emissions are projected to increase, but at a reduced rate when existing policies and measures are implemented, while implementation of additional mitigation measures targeting key source sectors would reduce $PM_{2.5}$ and $PM_{2.5}$ -precursor emissions.

The full implementation in different scenarios of Thailand's existing plans would reduce on $PM_{2.5}$, BC, OC, $NH_3$, NOx and $SO_2$ emissions by 33%, 25%, 37%, 5%, 12% and 17%, respectively in 2030 compared to a baseline scenario as shown in Table 5.9. The most effective of the existing individual mitigation measure was reducing the number of forest burned areas in the vegetation fires sector for reducing both $PM_{2.5}$ and OC emissions by 12% and 16%, respectively. However, changes in percentage emission reductions of additional measures have the largest potential to reduce $PM_{2.5}$ and its precursors emissions. Implementation of the additional measures was estimated to reduce $PM_{2.5}$, BC, OC, $NH_3$, NOx and $SO_2$ emissions by 70%, 58%, 78%, 32%, 23% and 28%, respectively in 2030 compared to a baseline scenario as shown in Table 5.9.

Finally, the most efficient measures of emission reductions for $PM_{2.5}$ and its precursors are from the additional scenarios which are achieved mostly through action in the residential sector for increasing use of clean fuels for cooking by replacing traditional stoves from charcoal, wood and vegetal.

**Table 5.8:** National total emissions (kt) of $PM_{2.5}$ and its precursors in 2030 from implementing each mitigation scenario compared to the 2030 baseline scenario in Thailand

| Scenario | Source Sector | Measure | $PM_{2.5}$ | BC | OC | $NH_3$ | NOx | $SO_2$ |
|---|---|---|---|---|---|---|---|---|
| **Measure 1 Existing: HDV Euro 5 by 2023** | Transport | Increasing Euro 5 vehicles standard | 529.7 | 82.9 | 224.5 | 812.8 | 1,622.2 | 1,169.3 |
| **Measure 1 Existing: LDV Euro 6 by 2023** | Transport | Increasing Euro 6 vehicles standard | 522.3 | 75.6 | 224.0 | 809.8 | 1,722.0 | 1,168.9 |
| **Measure 9 Existing: Vegetation Fires** | Vegetation fires | Reducing the number of forest burned areas | 467.7 | 79.8 | 187.9 | 803.6 | 1,743.2 | 1,164.9 |
| **Measure 11 Existing: Power Development Plan** | Electricity generation | Increasing renewable energy | 506.9 | 83.8 | 221.8 | 812.8 | 1,672.9 | 1,034.1 |
| **Measure 2 Additional: Clean fuel for cooking** | Residential | Replacing traditional charcoal stove with clean fuel for cooking | 419.3 | 69.0 | 171.7 | 793.8 | 1,736.4 | 1,150.6 |
| **Measure 3 Additional: Clean fuel for cooking** | Residential | Replacing traditional wood stove with clean fuel for cooking | 419.3 | 69.0 | 171.7 | 793.8 | 1,736.4 | 1,150.6 |
| **Measure 4 Additional: Clean fuel for cooking** | Residential | Replacing traditional vegetal stove with clean fuel for cooking | 419.3 | 69.0 | 171.7 | 793.8 | 1,736.4 | 1,150.6 |
| **Measure 5 Additional: Clean fuel in industry** | Industry | Reducing brown coal briquettes use in industry | 492.7 | 76.3 | 207.5 | 813.3 | 1,744.9 | 1,062.8 |
| **Measure 6 Additional: Clean fuel in industry** | Industry | Reducing primary solid biomass use in industry | 492.7 | 76.3 | 207.5 | 813.3 | 1,744.9 | 1,062.8 |
| **Measure 7 Additional: Crop Burning** | Agriculture | Banning crop residue burning | 464.2 | 78.2 | 184.0 | 783.2 | 1,731.3 | 1,164.9 |
| **Measure 8 Additional: Reducing $NH_3$ from Agriculture** | Agriculture | Replacing urea with the other complex NK and NPK fertilizers use in agriculture | 532.1 | 84.5 | 224.7 | 616.4 | 1,760.5 | 1,168.9 |
| **Measure 10 Additional: Ban Waste Burning** | Waste | Banning open waste burning | 488.4 | 81.6 | 201.3 | 807.8 | 1,738.7 | 1,166.7 |
| **Baseline** | | | **532.1** | **84.5** | **224.7** | **812.8** | **1,760.5** | **1,168.9** |
| **Existing plans (All measures)** | | | **358.3** | **63.4** | **142.7** | **770.9** | **1,554.1** | **966.0** |
| **Additional plans (Additional measures)** | | | **160.3** | **35.6** | **48.7** | **550.9** | **1,359.9** | **839.7** |

**Table 5.9:** Summary of percentage emission reductions from implementing mitigation measures modelled in different scenarios for Thailand compared to the 2030 baseline scenario

| Scenario | Source Sector | Measure | $PM_{2.5}$ (%) | BC (%) | OC (%) | $NH_3$ (%) | NOx (%) | $SO_2$ (%) |
|---|---|---|---|---|---|---|---|---|
| **Measure 1 Existing: HDV Euro 5 by 2023** | Transport | Increasing Euro 5 vehicles standard | -0.4 | -2 | -0.1 | - | -8 | - |
| **Measure 1 Existing: LDV Euro 6 by 2023** | Transport | Increasing Euro 6 vehicles standard | -2 | -11 | -0.3 | -0.4 | -2 | - |
| **Measure 9 Existing: Vegetation Fires** | Vegetation fires | Reducing the number of forest burned areas | -12 | -6 | -16 | -1 | -1 | -0.3 |
| **Measure 11 Existing: Power Development Plan** | Electricity generation | Increasing renewable energy | -5 | -1 | -1 | - | -5 | -12 |
| **Measure 2 Additional: Clean fuel for cooking** | Residential | Replacing traditional charcoal stove with clean fuel for cooking | -21 | -18 | -24 | -2 | -1 | -2 |
| **Measure 3 Additional: Clean fuel for cooking** | Residential | Replacing traditional wood stove with clean fuel for cooking | -21 | -18 | -24 | -2 | -1 | -2 |
| **Measure 4 Additional: Clean fuel for cooking** | Residential | Replacing traditional vegetal stove with clean fuel for cooking | -21 | -18 | -24 | -2 | -1 | -2 |
| **Measure 5 Additional: Clean fuel in industry** | Industry | Reducing brown coal briquettes use in industry | -7 | -10 | -8 | 0.1 | -1 | -9 |
| **Measure 6 Additional: Clean fuel in industry** | Industry | Reducing primary solid biomass use in industry | -7 | -10 | -8 | 0.1 | -1 | -9 |
| **Measure 7 Additional: Crop Burning** | Agriculture | Banning crop residue burning | -13 | -7 | -18 | -4 | -2 | -0.3 |
| **Measure 8 Additional: Reducing $NH_3$ from Agriculture** | Agriculture | Replacing urea with the other complex NK and NPK fertilizers use in agriculture | - | - | - | -24 | - | - |
| **Measure 10 Additional: Ban Waste Burning** | Waste | Banning open waste burning | -8 | -3 | -10 | -1 | -1 | -0.2 |
| **Existing plans (All measures)** | | | **-33** | **-25** | **-36** | **-5** | **-12** | **-17** |
| **Additional plans (Additional measures)** | | | **-70** | **-58** | **-78** | **-32** | **-23** | **-28** |

Previous studies have developed emission inventories for different base years and different source sectors in Thailand. Vongmahadlek *et al.* (2009) estimated the national annual emissions of air pollutants from all sources across Thailand for the year 2005. The total emissions were generally consistent with this study as shown in Table 5.6. However, $NO_x$ emissions were different because of the number of vehicles increased from 196,557 in 2005 to 219,105 in 2010 (12%) (DLT, 2005; DLT 2010). Other studies estimating national emissions in Thailand have focussed on a specific source sector. Emission from crop residue open burning in Thailand for the year 2010 from Kim Oanh *et al.* (2018) found that the emissions were also consistent with this study in agricultural sector in 2010 as shown in Table 5.6. However, $NH_3$ emissions showed the largest difference in values because this study included estimates of emissions from fertilizer application, which were not quantified in the agricultural sector emissions in Kim Oanh et al. (2018).

Kanabkaew and Kim Oanh (2011) reported that annual emissions of $PM_{2.5}$, $SO_2$, $NO_x$, and $NH_3$ in Thailand in the base year of 2007 from crop residue field burning in kt $yr^{-1}$ were 128, 4, 42, and 59, respectively (Table 5.6). All pollutants from Kanabkaew and Kim Oanh (2011) study were higher than this study because of the differences of base years (2007 and 2010, where there were different extents of biomass burned in northern Thailand, where the majority of crop residue burning occurs, as shown by remote sensing measurements **(**Huang *et al.*, 2016**),** and assumptions about the fraction of crop residues burned in fields). Specifcially, in 2007, the base year for the Kanabkaew and Kim Oanh 2011 study, The influence of biomass burnings from agricultural waste and forest fires were identified for major sources of $PM_{2.5}$ emissions (Vongruang, Wongwises and Pimonsree, 2017; Khamkaew, Chantara and Wiriya, 2016; Kim Oanh *et al.*, 2011) which is consistent with this work that emitted 17% from agricultural sector and 11% from forest fires.

This study $PM_{2.5}$ concentration and $PM_{2.5}$ precursors are emitted from natural background, as well as from anthropogenic sources in Thailand and in the rest of the world. The contribution of $PM_{2.5}$ precursors to $PM_{2.5}$ concentration levels from these sources after implemented the additional mitigation measures would reduce the largest proportion of $PM_{2.5}$ concentrations in 2030 compared to the baseline scenarios in 2010. $NH_3$ and $NO_x$ also make the largest contribution to national emissions, therefore measures that focus on major sources of $NH_3$ (agriculture) and $NO_x$ (transport) should all be considered to reduce $PM_{2.5}$ concentration. However, the emissions from outside Thailand

(rest of the world) showed the large proportion as well and still needed to target further. The emissions from natural background are also important but it could not control. In addition, the implementation of existing measures could avoid increasing of $PM_{2.5}$ emissions compared to the baseline scenario but with a small proportion compared to the additional mitigation measures. Overall, the $PM_{2.5}$ concentration reduction when existing measures and baseline scenarios were implemented are expected to increase in 2030. However, $PM_{2.5}$ concentrations from additional measures compared to the baseline scenarios in 2010 is expected to reduce in 2030.

Previous studies also found that national emissions or anthropogenic sources showed the large contribution than the rest of world emissions (such as neighbouring countries emissions). $NH_3$ and $NO_x$ were emitted from Thailand with the largest proportion, for example, $NO_x$ from biomass open burning (Cheewaphongphan and Garivait, 2013) and transport sector (Cheewaphongphan *et al.*, 2017), $NH_3$ and $NO_x$ from power plants and industrial facilities in Thailand (Pham, Manomaiphiboon and Vongmahadlek, 2008) that are consistent with this study. The reduction in $PM_{2.5}$ concentrations and $PM_{2.5}$ precursors from all sources are expected to reduce from national emissions when implementing the additional measures.

Based on the health impacts from previous studies, exposure to $PM_{2.5}$ from both short-term and long-term are associated with mortality (for example Shi *et al.*, 2016; Beelen, Andersen and Wolf, 2013; Anenberg *et al.*, 2011). Few studies on mortality have been conducted in Thailand. Ostro, *et al.* (1999) reported the relationship between $PM_{10}$ and daily mortality during 1992 – 1995 in Bangkok, Thailand. The results showed that a 10 μg $m^{-3}$ change in daily $PM_{10}$ is associated with a 1–2% increase in natural mortality, a 1–2% increase in cardiovascular mortality, and a 3–6% increase in respiratory mortality. The study from Vichit-vadakan, Vajanapoom, and Ostro (2008) also reported that the mortality risk due to long-term exposure to $PM_{10}$ from 1999 to 2003 in Bangkok. The results showed that the excess risk for non-accidental mortality was 1.3% per 10 μg $m^{-3}$ of $PM_{10}$, with higher excess risks for cardiovascular 1.9% and above age 65 mortality 1.5%. A similar finding in Thailand during 1999–2008 from Guo *et al.* (2014) reported that an increase of 10 μg $m^{-3}$ in $PM_{10}$ was associated with a 0.4% increase of non-accidental mortality. Whereas, the increase of respiratory mortality was 0.4% and the increase of cardiovascular was 0.1% (Guo *et al.*, 2014). In this study there were estimated 27,560 of premature deaths in Thailand associated with air pollution exposure in 2017.

This study is consistent with the Global Burden of Disease study. The Global Burden of Disease study 2017 estimated that 30,635 premature deaths were attributable to $PM_{2.5}$ exposure from air pollution in Thailand (GBD, 2017) which is consistent to this study in baseline scenarios in 2017 (27,560).

In this study found that exposure to $PM_{2.5}$ is associated with increased mortality in the sensitive groups age over 70 years that expected to increase in the future, additional measures are need to apply in order to reduce the risk of $PM_{2.5}$ exposure.

## 5.5 Uncertainties

In this analysis, as in any integrated assessment modelling exercise, a large volume of data needs to be compiled in order to be able to estimate emissions of pollutants historically, to project these emissions into the future, and to assess the impact of these emissions on air pollution exposure and consequential health impacts. The data and methods used to undertake this analysis have different levels of confidence and uncertainty associated with them. There are multiple sources of uncertainty in this analysis, of which the key sources are highlighted and discussed below. In many cases official data specific to Thailand was used to estimate emissions, but where Thailand-specific data was not available, data measured/obtained in other countries and other regions was applied to estimate emissions in Thailand. There is therefore uncertainty in the application of international data, such as emission factors, concentration-response functions etc. derived in studies conducted in other countries. Finally, there is uncertainty in the methodologies within which this data is applied. Most importantly, the methods for converting air pollutant emissions into the estimate exposure of the Thai population.

The aim of this analysis was to explore the contribution of different source sectors to air pollutant emissions in Thailand, how this contribution is likely to change into the future and how the implementation of mitigation measures in key source sectors can help to reduce $PM_{2.5}$ concentrations in Thailand. As shown above, the results obtained using the data and methods in this analysis are similar to those obtained in previous studies, and the future projections are based as far as possible on official data produced by the Thai government or international organisations (e.g. population and GDP projections which are key variables determining the trajectory of emissions into the future). Therefore, while

the improvement of data used as input to this analysis would increase the accuracy of the results, it is not expected that it would change the overall conclusions of this analysis in terms of the overall emission reductions and benefits expected from implementation of the mitigation measures evaluated in this study.

The key uncertainties and limitations for this analysis, and how they could be reduced, are described in more detail in the subsection below.

### 5.5.1 Emission factors (EFs)

Due to limitation of country-specific EFs data that are needed to identify the major sources of emissions in Thailand, in this study EFs were taken from international sources as shown in Appendix (Table S22 – S36). These were predominantly from international guidebooks on emission inventory development, such as the EMEP/EEA 2016 emission inventory guidebook developed for Europe, and which is endorsed by the Intergovernmental Panel on Climate Change to estimate emissions from air pollutants globally in the absence of other data. The use of emission factors from studies conducted in Europe and other regions to Thailand may not reflect locally available equipment, or how it is used in Thailand which may mean that the emissions are different compared to comparable activities in Europe or other regions where the emission factors were measured.

However, the lack of Thailand specific emission factors has been highlighted in other studies, which have also relied on international default emission factor data. For example, Cheewaphongphan *et al.* (2017) used EF from the GAINS-Asia database to estimate an emission inventory of on-road transport in Bangkok Metropolitan Region (BMR). Vongruang, Wongwises and Pimonsree (2017) also applied the EFs that reported from Kaiser *et al.*, 2012 and Wiedinmyer *et al.*, 2011 to assess fire emission inventories of $PM_{10}$ in upper Southeast Asia (e.g. Thailand, Myanmar, Vietnam etc.). Another study from Junpen, Garivait and Bonnet (2013) estimated emissions from forest fires in Thailand using MODIS active fire product and country specific data with the EFs of tropical forests as reported by Andrea and Merlet (2001). As shown in the previous section, the results obtained in this study are comparable with those calculated previously using these alternative emission factor sources. In order to improve emission inventory

development in Thailand, more studies need to be undertaken in Thailand, or South East Asia to measure emissions from key sources.

### 5.5.2 Activity data

The activity data used to estimate emissions in this study was obtained as far as possible from official government statistics. This study used Thai official data for specific sectors in energy sector from the Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy, waste management such as solid waste generated and disposed that reported by the Pollution Control Department (PCD), Ministry of Natural Resources and Environment and transport sector from Department of Land Transport, Ministry of Transport. In some cases, in the absence of official Thai data, Thailand data from international databases was used to estimate activity in specific sectors. This includes data from the FAOSTAT database to represent activity in agriculture (livestock, crop production) and vegetation fires (annual area burned). In these latter cases the activity data for Thailand from these international databases should be improved through the provision of nationally-derived data, and/or comparison with measurement data. For example, satellite data on vegetation fires and crop residue burning could be used to validate the bottom-up activity data derived for these sources, as has been done previously in other regions.

### 5.5.3 Baseline scenario

The progression of emissions between 2010 and 2030 without the implementation of mitigation measures was assumed to develop based on a variety of assumptions, including expected changes in demographics (population) and socioeconomic development (GDP), the continuation of historical trends in energy intensity reductions, and on regional trend projections. Uncertainties associated with the baseline scenario include the use of an average GDP growth rate. In reality GDP may fluctuate and be higher or lower than the expected estimates, affecting the total emissions from Thailand in the future. Regional projections for different variables (such as livestock numbers and crop production) may not reflect the specifics of these sectors in Thailand. These uncertainties in the baseline scenario assumptions would not affect the conclusions of this analysis in terms of the

most effective mitigation measures that could be taken by Thailand to improve air quality, given that all mitigation measures are evaluated from a common baseline scenario.

### 5.5.4 Air pollution health impact assessment

The conversion of emissions of different pollutants to concentrations of $PM_{2.5}$ that people are exposed to in this study relied on a set of coefficients developed using the GEOS-Chem Adjoint model. They are 'linear coefficients, which means that a change in emissions results in a linear increase/decrease in $PM_{2.5}$ concentrations in the target country. This means that non-linear atmospheric chemistry, such as formation of secondary inorganic aerosol formation, is represented by a linear relationship. For moderate changes in emissions, this approach has been shown to provide a reasonably accurate estimate of $PM_{2.5}$ concentrations from emissions of different pollutants (Xu *et al.,* 2013; Henze, Seinfeld and Shindell, 2009; Henze *et al.*, 2007).

In addition, the representation of atmospheric chemistry in the atmospheric coefficients is at the scale of 2x 2.5 degrees. This means that atmospheric chemical processing at scales smaller than this are not represented within the modelling approach used to calculate $PM_{2.5}$ concentrations, and that emissions within each 2 x 2.5 degree grid are assumed to result in the same change in $PM_{2.5}$ concentrations across Thailand. The effect of grid size on air pollution health impact estimates has been assessed previously, and has been shown to affect results up to approximately 6% when grid squares are varied from 12 km estimate at > 250 km resolution (Punger and West, 2013).

Finally, the concentration-response function used to convert $PM_{2.5}$ into health impacts, the Integrated Exposure Response (IER) function (Burnett *et al.,* 2014), was derived by integrating epidemiological studies that quantify the relationship between $PM_{2.5}$ exposure and risk of premature deaths from ambient $PM_{2.5}$, household air pollution, secondhand smoke, and active smoking. Almost all of the studies of ambient air pollution were conducted in North America and Europe (with one study conducted in China). In these locations $PM_{2.5}$ concentrations are typically lower than in Thailand, and therefore an assumption in application of this health impact assessment approach is that the same concentration-response function for European and North Americans applies to people in Thailand. A further assumption in applying this approach is that it is the overall mass of $PM_{2.5}$ that affects health, and that $PM_{2.5}$ of different composition has the same effect on

health. While there is evidence that some components differ in their toxicity, the WHO concluded (WHO, 2013) that the evidence was insufficient to attribute the health impact to any one $PM_{2.5}$ component and that the $PM_{2.5}$ mass concentration was the best metric to use for assessing health risks.

## 5.6 Implications for reducing air pollution in Thailand

Based on the analysis in this study current (2010) emission of air pollutants resulted in a population-weighted $PM_{2.5}$ concentrations across Thailand of 28.5 μg $m^{-3}$. This level of exposure was estimated to be associated with 22,378 number of premature deaths in 2010. The first implication from this study is that without the implementation of additional policies and measures, the expected socioeconomic development of Thailand (IE growth in population and GDP) will increase emissions of air pollutants, the concentrations that people exposed to and the health impacts associated with them.

Thailand has developed plans and strategies in many of the key sectors that emit air pollutants. These include the energy efficiency plan, the renewable energy plan, plans to reduce burning of forest fires, power development plan and Thai roadmap for Euro 5/6 standards. This analysis shows that the full implementation of the measures that are included in these plans are effective in reducing air pollution emissions, and will contribute to avoiding the expected increase in air pollution concentrations. However, these measures alone will not substantially reduce air pollution concentrations on average across Thailand below 2010 level. This means that after the full implementation of current plans $PM_{2.5}$ concentrations will still substantially exceed the WHO air quality guideline and have significant impacts on cardiovascular and respiratory mortality. In addition, the health impacts from the same level of air pollution exposures are projected to increase due to the larger population in Thailand being exposed and due to an aging population (older people are more sensitive to cardiovascular and respiratory diseases).

Therefore, in order to reduce air pollution and its health impacts further, Thailand needs to implement additional measures in key source sectors. After the implementation of all current plans there are still large emissions from industry, residential, agriculture, transport and waste. Further actions in these sectors could substantially reduce emissions of pollutants contributing to $PM_{2.5}$ concentrations. Therefore, Thailand should consider

how action to reduce $NO_X$ emission from transport, $NH_3$ emission from agriculture, and particulate (BC, OC) emission from industry and residential can be included in current plans. However, the reduction in emissions in Thailand from the additional actions in these sectors will not be enough to reduce population-weighted $PM_{2.5}$ across Thailand below the WHO air quality guideline. This is because not only do emissions in Thailand contribute to $PM_{2.5}$ concentrations that people in Thailand are exposed to but emissions from neighbouring countries and natural sources also contribute. In 2010 the contribution to $PM_{2.5}$ concentrations in Thailand from neighbouring countries emission was estimated to be approximately one-third. This analysis focused only on reducing emissions from sources within Thailand and not action to reduce emissions from other countries. However, a key implication from this study is that regional action to reduce emissions across all countries in SEA is necessary for $PM_{2.5}$ concentrations across Thailand to meet WHO guideline to protect human health.

## 5.7 Conclusion

The aim of this study was to apply a modelling framework to understand the link between emissions from different source sectors and geographic region (Thailand and neighbouring countries) and annual average $PM_{2.5}$ concentration across Thailand. This framework was applied for historical years (2010 – 2017) and for future years projected from 2018 to 2030. These projections accessed a business as usual progression based on GDP and population growth as well as projections accounting for implementation of current government plans and policies and the implementation of the additional actions in key emission source sectors in Thailand.

The findings from this study show that $PM_{2.5}$ and its precursors emissions are projected to decrease by 2030 when key mitigation scenarios from difference source sectors are implemented. To improve air quality and to achieve low emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors, this study suggests implementing the appropriate mitigation measures to reduce $PM_{2.5}$ and precursors emissions so that policy-making and pollution control authorities can tackle the air pollution problems related to different source sectors. The health benefits will be significant when the suggested measures are fully implemented to reduce $PM_{2.5}$ concentration associated with health risk.

# Chapter 6: Conclusions and Implications for Policy

## 6.1 Introduction

In Thailand, several measurement and modelling studies have been conducted previously that have provided information on the sources and spatial distribution of particulate matter (PM) air pollution (Punsompong and Chantara, 2018; Phayungwiwatthanakoon, 2013; Ruanngern, 2012; Kim Oahn and Leelasakultum, 2011). For example, the major sources of particulate matter in Thailand come from different source sectors. During the dry season the Bangkok metropolitan region (February) and the Northern region of Thailand (March) have a large accumulation of air pollution every year. Generally, high levels of particulate matter occur in large cities with heavy traffic, and are associated with open burning activities, agriculture, and industrial areas. (PCD, 2019). However, as outlined in Chapter 1, many of these studies have focussed on a specific sub-region of Thailand (e.g. Bangkok, or northern Thailand), or on a particular time of the year, i.e. during the time when the short-term peak PM concentrations occur.

Based on these previous studies, there are several limitations to the knowledge of PM and its variation across the whole of Thailand that this thesis has attempted to overcome. The focus of this thesis has been on the determinants of the *annual average* PM concentration that occurs in different areas of Thailand. While many studies have focused on the geographic and sectoral sources of short-term peak in PM, few studies have investigated how the annual average PM concentration is determined across the whole of Thailand, and what can be done to reduce annual average PM concentrations. This is despite the annual average PM concentration being the PM concentration metric that is most associated with negative effects on human health (because it is a proxy for long-term exposure to PM, in contrast to hourly or daily averages which represent short-term exposure).

Therefore, the core aim of this thesis was to investigate annual average PM across the whole of Thailand using measurement and modelling approaches to analyse:

i) the magnitude of annual $PM_{10}$ concentrations across Thailand, identifying those locations where concentrations were highest;
ii) the variation in hourly PM concentrations that produce annual PM concentrations, and the drivers of this variation including different geographic and sectoral sources; and
iii) to assess the options and strategies that Thailand could pursue to reduce annual average PM concentrations, and the health impacts associated with them.

## 6.2 Key conclusions from study

The key conclusions that are most important to highlight from this thesis relate to the exceedance of the Thai annual average PM standard, and WHO air quality guideline for annual average PM, and which draw on the results from multiple Chapters. The key conclusions are that: i) while biomass burning increases hourly $PM_{10}$ concentrations in northern Thailand, this also causes the exceedance of the Thai national standard for annual average $PM_{10}$, especially in Northern Thailand; ii) Thailand cannot meet the annual PM WHO guidelines alone, and cooperation to reduce the contribution from transboundary transport is needed to reduce PM to below these levels; and iii) additional actions on top of those included in Thailand's current plans are required to reduce annual $PM_{2.5}$ concentrations in the future.

### 6.2.1 Key Conclusion 1: Biomass burning periods contribute to exceedance of Annual Thai national standard

Biomass burning, i.e. the burning of crop residues in preparation for the new crop growing season, occurs during specific periods of the year. In Northern Thailand (and neighbouring countries such as Myanmar), the biomass burning period is centred on March, while further south (in Thailand and neighbouring countries such as Malaysia), the biomass burning period occurs during October (PCD, 2016).

The key implication from this study is that, in northern Thailand, not only does the biomass burning period during March result in short-term peaks in hourly or daily average $PM_{10}$ concentrations, as shown in previous studies (see Chapter 3), it also makes a substantial contribution in determining the magnitude of annual average $PM_{10}$ concentrations in this region. Importantly, the additional contribution of biomass burning to annual average $PM_{10}$ concentrations was shown to result in a larger number of exceedances of the Thai National Standard for annual average $PM_{10}$ concentrations than in other regions of Thailand. This additional contribution of biomass burning to annual average $PM_{10}$ also made northern Thailand the region with the highest annual average $PM_{10}$ concentrations and the greatest exceedance of the WHO air quality guideline (on average across sites in the region, isolated sites in central Thailand had higher annual $PM_{10}$ concentrations).

This implication that biomass burning contributes to the exceedance of the Thai national annual average $PM_{10}$ standard demonstrates clearly how the chemical climatology framework contributes to increasing the information that is gained from analysis of an air quality monitoring network. The standard set of 'chemical climatology' statistics calculated, consistently across all sites in northern Thailand over a 5-year study period provided multiple indicators demonstrating the substantial contribution that biomass burning made to determining the level of annual $PM_{10}$ concentrations at sites across northern Thailand. Firstly, calculating the contribution of different months to annual average $PM_{10}$ showed that March, when biomass burning occurs made a disproportionate contribution. Secondly, the highest hourly $PM_{10}$ concentrations (>95$^{th}$ percentile) at sites in Northern Thailand, a) contributed approximately 20% to annual average $PM_{10}$ concentrations, and b) occurred almost exclusively during the biomass burning periods. Finally, the calculation of these statistics over multiple years showed that during years in which previous studies have shown emissions from biomass burning to be substantially lower (2011, due to the influence of La Nina), showed that i) the magnitude of very high concentrations were lower, ii) they occurred less during March, and iii) their contribution to the annual average $PM_{10}$ concentration was less, indicating a lower contribution of biomass burning to determining the annual average $PM_{10}$ concentration during this year. This coincided with no sites exceeding the Thai national standard for $PM_{10}$ under these conditions. Therefore, this thesis demonstrates that actions that can reduce the level of biomass burning in northern Thailand could avoid exceedance of the Thai national standard on annual average $PM_{10}$.

### 6.2.2 Key Conclusion 2: Reducing transboundary transport necessary to meet WHO annual PM guideline

The analysis of monitoring data between 2011 and 2015 showed that all sites in Thailand exceeded the WHO guideline value for annual average $PM_{10}$. The air pollution modelling conducted in Chapter 5 estimates that, as a population-weighted value, annual average $PM_{2.5}$ concentrations were 3 times higher than the WHO air quality guideline for annual average $PM_{2.5}$. A key conclusion from this study is that both measurement and modelling analyses indicate that there is a substantial contribution to annual average PM concentrations in Thailand that is determined by transboundary transport and emission sources outside of Thailand.

The analysis of monitoring data, coupled with air mass back trajectory analysis, show an increase in hourly $PM_{10}$ concentrations associated with air masses that spend more time over Myanmar (as well as northern Thailand) in the 4 days prior to arrival at sites in northern Thailand. As stated above, the very high concentrations associated with these conditions make a substantial contribution to annual $PM_{10}$ concentrations, and to the exceedance of the Thai national standard. In addition, in southern Thailand, air mass back trajectory analysis shows that during certain times of the year air masses traversing Malaysia and Indonesia result in very high hourly $PM_{10}$ concentrations occurring at sites in southern Thailand. This provides regionally specific information based on an analysis of actual measured concentrations. However, the coincidence of air masses pathways with elevated PM concentrations at measurement sites does not allow the percentage contribution of emissions, e.g. from biomass burning in Myanmar vs northern Thailand, to be determined.

The modelling of population-weighted annual average $PM_{2.5}$ concentrations across Thailand provides more information on the specific contribution of Thailand's emissions compared to emissions in the rest of the world. In 2010, it was estimated that 35% of population-weighted $PM_{2.5}$ concentrations resulted from emissions occurring outside of Thailand. When accounting for the reductions in $PM_{2.5}$ and $PM_{2.5}$-precursor emission achievable in Thailand, the modelling in Chapter 5 also showed that (and a population-weighted average) annual $PM_{2.5}$ concentrations across Thailand could not reduce below the WHO air quality guideline without reductions in emissions in neighbouring countries. While further work is required to disaggregate the sources, strategies and measures

needed to reduce emissions from sources outside Thailand that would most effectively reduce Thailand's annual $PM_{2.5}$ concentrations, the chemical climatology analysis of Thailand's monitoring network shows that biomass burning in Myanmar could be a key external source.

To prevent and monitor transboundary haze pollution in ASEAN countries, the ASEAN Agreement on Transboundary Haze Pollution (AATHP) was established in 2002 under ASEAN member states, aimed to prevent and monitor transboundary haze pollution from land and/or forest fire with international co-operation in this region. Then in 2016 the ASEAN Agreement on Transboundary Haze-Free Roadmap was created with the aim of Transboundary Haze Pollution problem solving in ASEAN, aiming for a Haze-free ASEAN by 2020, as well as a collaboration with neighbouring countries for sustainable haze solution. This study shows that implementation of the ASEAN agreement and the haze free road map is essential to reduce population-weighted $PM_{2.5}$ concentration across Thailand to meet WHO air quality guidelines, based on the modelling Chapter 5, and to reduce $PM_{10}$ concentrations at sites in northern Thailand to comply with the national air quality standards, based on the analysis in Chapter 3.

### 6.2.3 Key Conclusion 3: Additional actions required to reduce annual PM in the future

Key implication 2 implies that additional action is required in countries outside of Thailand to reduce annual average PM concentrations within Thailand. The third key implication is that within Thailand, additional actions are needed, on top of what the Government has already planned, to be able to reduce annual PM concentrations below their current levels.

The assessment of monitoring data, as stated above, shows that there is exceedance of the Thai national standards for annual $PM_{10}$ concentrations, and widespread exceedance of the WHO ambient air quality guideline for annual PM. The modelling in Chapter 5 projected that the annual PM concentrations are likely to deteriorate further in the future without intervention to control emission sources, due to expected growth in population and the Thai economy.

In addition, the Thai government has outlined a series of plans, and policies that will affect emissions compared to this 'business as usual' projection such as a 20-year master plan for air quality management (2018-2037) that has been developed, which aims to reduce and control pollution emissions such as elevating the standards of exhaust for new vehicles with launch zero emission regulations, improvement in fuel qualities, adopt an eco-industrial system and green industrial standards, promote burn-less agricultural activities and set up air quality monitoring stations to cover all provinces across the country (PCD, 2019).

Moreover, the Ministry of Natural Resources and Environment of Lao PDR and Thailand had a cooperation on natural resources and environment with plan of action on pollution control and supporting of air quality monitoring station to Lao PDR, including mobilization of mobile unit of air quality monitoring for neighboring countries such as Lao PDR, Myanmar and Cambodia.

However, this study shows that the implementation of the government plans, and achievements of targets already set will only be sufficient to avoid the projected increase in population-weighted annual PM concentrations, keeping annual PM at its current concentrations. However, further interventions, in addition to those in existing plans, are required, within Thailand and outside of Thailand, to reduce population-weighted annual $PM_{2.5}$ concentrations below their current level. Based on the analysis in Chapter 5, the additional actions that are most effective in reducing population-weighted $PM_{2.5}$ further are ban crop burning with zero fraction burned in field by 2030 in agriculture sector, follow by replace traditional stove wood with clean fuel for cooking with zero people cook with traditional stove wood and vegetal wastes by 2030 and in residential sector, and zero waste burning by 2030 in waste sector.

## 6.3 Next steps and future work

This thesis has shown that further statistical analysis of available air quality monitoring data can increase the information obtained on the geographic and sectoral sources determined key air pollution metrics (i.e. annual average $PM_{10}$) relevant for human health. It has also demonstrated how combining analysis of monitoring data with modelling future changes in emissions in response to the implementation of different policies can be used to assess how the PM concentrations monitored today can be reduced. However, as described in Chapters 3, 4 and 5, there are limitations and uncertainties associated with both the monitoring, and modelling components of this thesis. Based on these limitations, as well as the key implications of this work, there are two key areas where additional work would build on the results of this thesis and extend the ability to: i) monitor and analyse the conditions producing annual PM concentrations in Thailand, especially in those locations that may exceed Thai national air quality standards; and ii) model and evaluate the most effective strategies to reduce PM across Thailand.

### 6.3.1 Expansion of the air quality monitoring network in Thailand

As outlined in Section 6.2.1, the calculation of a standard set of chemical climatology statistics at all monitoring sites across Thailand has increased the information on the determinants of annual average $PM_{10}$ concentrations across Thailand. The composition of Thailand's air quality monitoring network has several advantages that have facilitated this assessment. Firstly, there are monitoring sites in diverse regions of Thailand, allowing comparison between northern, southern and central Thailand. Secondly, data is monitored and published at hourly time resolution allowing hourly variation across the day (e.g. during rush hour and non-rush hour periods) to be assessed. However, there are also several limitations to the current air quality monitoring network, and areas where, if addressed, could substantially enhance the ability to analyse the conditions (geographic and source sector contributions, meteorological conditions, local vs long-range transport) producing annual average PM concentrations. These areas include:

- Expand monitoring of $PM_{2.5}$: Currently monitoring of $PM_{2.5}$ occurs at sites located in Bangkok and some provinces, with $PM_{10}$ concentrations monitored more widely across Thailand. This has meant that in this analysis of PM across Thailand

using monitoring data we have relied on $PM_{10}$ for a consistent representation of PM measurements across Thailand. In terms of effects on human health, $PM_{2.5}$ is the metric that is more strongly associated with negative health impacts (WHO, 2013), even though concentrations of $PM_{10}$ and $PM_{2.5}$ are strongly correlated. Therefore, monitoring $PM_{2.5}$ concentrations more widely would allow for a characterisation of the drivers of variation in annual concentrations of this more health-relevant pollutant metric to be assessed.

- Expand monitoring to other site locations: Currently all of the sites monitoring PM in Thailand are located in cities, and their classification is separated between General and Roadside sites. This means that sites have not been located in other areas which could provide additional information on how annual PM varies spatially across Thailand, and the contribution of different sources and geographic regions. Firstly, roadside sites are only located in Bangkok. Having a larger number of roadside sites in other Thai cities would allow the annual PM increment at roadside sites in other locations to be determined, as well as the contribution of road transport as a source in these regions. Secondly, studies in Europe and elsewhere have compared the concentrations measured outside a city to those measured at sites in a city to assess the contribution of emissions in the city, and outside the city, to annual PM concentrations at different sites. This is not possible in Thailand due to a lack of rural monitoring stations. Adopting a site classification system similar to those used in Europe, in which sites are classified according to a combination of their area (urban, suburban and rural), and type (traffic, industrial and background) would allow for a broader range of conditions to be monitored and assessed, providing a more comprehensive overview of spatial variation in annual $PM_{10}$ concentrations across Thailand.
- Expand assessment of co-emitted and precursor pollutants: At monitoring sites across Thailand, $PM_{10}$, and at some sites $PM_{2.5}$ is measured alongside other pollutants, including $NO_2$, $SO_2$, VOCs, and ozone. Assessment of the correlation in variation between PM measurements and these other pollutants would allow additional information about sources of PM to be identified.

### 6.3.2 Enhancing air pollution modelling assessments at sub-national scale

As well as enhancing the monitoring network and data analysis described in Section 6.3.1, the other future work that could substantially enhance the work that has been completed in this thesis is the further development of the modelling. Uncertainties and limitations of the modelling framework are highlighted in Chapter 5, and not repeated here. The further work proposed here is based on assessment of the monitoring data, which shows that there are different drivers, in terms of the contribution of different source sectors, and from local vs long-range transport in different regions of Thailand. To summarise, the different regions of Thailand analysed using the monitoring data showed the following characteristics:

- Northern Thailand: widespread exceedance of Thai national standard with a substantial contribution from long-range transport of emissions from biomass burning.
- Central Thailand and Bangkok: Isolated exceedances of Thai national standard driven by local sources such as industry and/or road transport emissions.
- Southern Thailand: Lower annual average PM concentrations that still exceed WHO air quality guideline. Short-term peak concentrations driven by long-range transport during biomass burning season. Annual average concentrations driven by local sources.

Despite these differences in the determinants of annual average PM concentrations based on the measurement, the modelling was conducted at a national scale, with the emission inventory developed as a national scale analysis, and annual $PM_{2.5}$ concentrations quantified as a national population-weighted average. This allowed the effectiveness of current and additional policies on annual $PM_{2.5}$ in Thailand as a whole to be evaluated, providing a national roadmap for how annual $PM_{2.5}$ concentrations could be reduced. However, it does not allow greater detail on where specific policies, or actions in specific source sectors would be more or less effective in reducing $PM_{2.5}$ concentrations. This additional information would be important so that a national set of policies and measures to improve air quality can be implemented in those regions where they will deliver the largest benefit.

The development of a regionally disaggregated analysis of emissions and $PM_{2.5}$ concentrations would therefore enhance the ability of the modelling framework applied in Chapter 5 to assess *where* in Thailand different action needs to be taken to effectively reduce $PM_{2.5}$ concentrations. It would allow differences in the policies and actions that need to be taken in different regions to be identified. To do this would require a substantial increase in the availability of data. Specifically, the data required to develop an emission inventory for each region would need to be generated (or identified in those places, e.g. Bangkok, where it may already be available). For example, this would require energy consumption and production to be disaggregated to a regional level, which is not currently officially reported by the Ministry of Energy.

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# Appendix

# Chapter 2

**Table S1:** The exposed population and baseline mortality rate for each age group and disease category in 2010 (GBD, 2017)

| Variable: Population: Activity Level (Million People) | |
|---|---|
| Scenario: Baseline | |
| Branch: Key\Demographics\Population | |
| Region: Region 1 | |
| Branch | **2010** |
| Population | 67 |
| | |
| Variable: Population Fraction: Activity Level (fraction) | |
| Scenario: Baseline | |
| Branch: Key\Demographics\Population Fraction | |
| Region: Region 1 | |
| Branch | **2010** |
| Less than 5 years | 0.0601 |
| Age 30 to 34 years | 0.0809 |
| Age 35 to 39 years | 0.0850 |
| Age 40 to 44 years | 0.0870 |
| Age 45 to 49 years | 0.0802 |
| Age 50 to 54 years | 0.0714 |
| Age 55 to 59 years | 0.0554 |
| Age 60 to 64 years | 0.0404 |
| Age 65 to 69 years | 0.0307 |
| Age 70 to 74 years | 0.0249 |
| Age 75 to 79 years | 0.0171 |
| More than 80 years | 0.0163 |
| | |
| Variable: Less than 5 years: Activity Level (rate) | |
| Scenario: Baseline | |
| Branch: Key\Disease Rates\ALRI Disease Rate | |
| Region: Region 1 | |
| Branch | **2010** |
| Less than 5 years | 0.0002 |
| | |
| Variable: Lung Cancer Rate: Activity Level (rate) | |
| Scenario: Baseline | |
| Branch: Key\Disease Rates\Lung Cancer Rate | |
| Region: Region 1 | |
| Branch | **2010** |
| Age 30 to 34 years | 0.00002 |
| Age 35 to 39 years | 0.00004 |
| Age 40 to 44 years | 0.00008 |

| | |
|---|---|
| Age 45 to 49 years | 0.00016 |
| Age 50 to 54 years | 0.00028 |
| Age 55 to 59 years | 0.00045 |
| Age 60 to 64 years | 0.00076 |
| Age 65 to 69 years | 0.00117 |
| Age 70 to 74 years | 0.00158 |
| Age 75 to 79 years | 0.00222 |
| More than 80 years | 0.00315 |
| | |
| Variable: Stroke Rate: Activity Level (rate) | |
| Scenario: Baseline | |
| Branch: Key\Disease Rates\Stroke Rate | |
| Region: Region 1 | |
| Branch | **2010** |
| Age 30 to 34 years | 0.0001 |
| Age 35 to 39 years | 0.0001 |
| Age 40 to 44 years | 0.0002 |
| Age 45 to 49 years | 0.0003 |
| Age 50 to 54 years | 0.0005 |
| Age 55 to 59 years | 0.0007 |
| Age 60 to 64 years | 0.0010 |
| Age 65 to 69 years | 0.0015 |
| Age 70 to 74 years | 0.0024 |
| Age 75 to 79 years | 0.0038 |
| More than 80 years | 0.0091 |
| | |
| Variable: COPD Rate: Activity Level (rate) | |
| Scenario: Baseline | |
| Branch: Key\Disease Rates\COPD Rate | |
| Region: Region 1 | |
| Branch | **2010** |
| Age 30 to 34 years | 0.00003 |
| Age 35 to 39 years | 0.00005 |
| Age 40 to 44 years | 0.00006 |
| Age 45 to 49 years | 0.00009 |
| Age 50 to 54 years | 0.00013 |
| Age 55 to 59 years | 0.00023 |
| Age 60 to 64 years | 0.00045 |
| Age 65 to 69 years | 0.00082 |
| Age 70 to 74 years | 0.00163 |
| Age 75 to 79 years | 0.00278 |
| More than 80 years | 0.00680 |

| Variable: Ischaemic Heart Disease Rate: Activity Level (rate) | |
|---|---|
| Scenario: Baseline | |
| Branch: Key\Disease Rates\Ischaemic Heart Disease Rate | |
| Region: Region 1 | |
| Branch | **2010** |
| Age 30 to 34 years | 0.0001 |
| Age 35 to 39 years | 0.0001 |
| Age 40 to 44 years | 0.0002 |
| Age 45 to 49 years | 0.0003 |
| Age 50 to 54 years | 0.0005 |
| Age 55 to 59 years | 0.0007 |
| Age 60 to 64 years | 0.0011 |
| Age 65 to 69 years | 0.0018 |
| Age 70 to 74 years | 0.0031 |
| Age 75 to 79 years | 0.0054 |
| More than 80 years | 0.0133 |

**Table S2:** Percentage of hours when hourly $PM_{10}$ concentrations were below the limit of detection across all sites between 2011 and 2015

| Site | Region | Province | Category | % Lower detection limit of $PM_{10}$ concentration in hour ( < 4.8 µg $m^{-3}$) |
|---|---|---|---|---|
| 1 | Central | Bangkok | General Site | 1.7 |
| 2 | Central | Bangkok | General Site | 0.5 |
| 3 | Central | Bangkok | General Site | 1.8 |
| 4 | Central | Bangkok | General Site | 1.3 |
| 5 | Central | Bangkok | General Site | 0.6 |
| 6 | Central | Bangkok | General Site | 2.2 |
| 7 | Central | Bangkok | General Site | 0.7 |
| 8 | Central | Bangkok | General Site | 0.5 |
| 9 | Central | Bangkok | General Site | 2.3 |
| 17 | Central | Bangkok | General Site | 2.1 |
| 18 | Central | Bangkok | General Site | 1.9 |
| 10 | Central | Bangkok | Roadside Site | 0.1 |
| 11 | Central | Bangkok | Roadside Site | 0.05 |
| 12 | Central | Bangkok | Roadside Site | 0.01 |
| 13 | Central | Bangkok | Roadside Site | 0 |
| 14 | Central | Bangkok | Roadside Site | 1.6 |
| 15 | Central | Bangkok | Roadside Site | 4.7 |
| 16 | Central | Bangkok | Roadside Site | 0.9 |
| 19 | Central | Nonthaburi | General Site | 1.6 |
| 20 | Central | Nonthaburi | General Site | 3.8 |
| 21 | Central | Pathumthani | General Site | 2.0 |
| 22 | Central | Samut Prakan | General Site | 1.2 |
| 23 | Central | Samut Prakan | General Site | 0.2 |
| 24 | Central | Samut Prakan | General Site | 1.3 |
| 25 | Central | Samut Prakan | General Site | 0.03 |
| 26 | Central | Samut Prakan | General Site | 1.4 |
| 27 | Central | Samut Sakhon | General Site | 3.0 |
| 28 | Central | Samut Sakhon | General Site | 0.5 |
| 29 | Central | Samut Sakhon | General Site | 5.0 |
| 47 | Central | Ratchaburi | General Site | 1.1 |
| 48 | Central | Ratchaburi | General Site | 6.8 |
| 49 | Central | Saraburi | General Site | 0.1 |
| 50 | Central | Saraburi | General Site | 2.8 |
| 51 | Central | Phra Nakhon Si Ayutthaya | General Site | 0.8 |
| 52 | East | Chachoengsao | General Site | 2.7 |
| 53 | East | Chachoengsao | General Site | 5.0 |
| 54 | East | Chon buri | General Site | 0.4 |
| 55 | East | Chon buri | General Site | 0.2 |
| 56 | East | Chon buri | General Site | 14.2 |
| 57 | East | Chon buri | General Site | 1.2 |
| 58 | East | Chon buri | General Site | 8.6 |

| Site | Region | Province | Category | % Lower detection limit of $PM_{10}$ concentration in hour ( < 4.8 µg $m^{-3}$) |
|---|---|---|---|---|
| 59 | East | Rayong | General Site | 1.2 |
| 60 | East | Rayong | General Site | 1.2 |
| 61 | East | Rayong | General Site | 1.9 |
| 62 | East | Rayong | General Site | 1.0 |
| 64 | East | Rayong | General Site | 0.8 |
| 65 | East | Rayong | General Site | 2.7 |
| 66 | East | Sa Kaeo | General Site | 2.9 |
| 67 | Northeast | Khon Kaen | General Site | 0.5 |
| 68 | Northeast | Khon Kaen | General Site | 1.6 |
| 69 | Northeast | Nakhon Ratchasima | General Site | 0.5 |
| 71 | Northeast | Loei | General Site | 3.3 |
| 72 | South | Narathiwat | General Site | 0.4 |
| 73 | South | Phuket | General Site | 2.5 |
| 74 | South | Yala | General Site | 1.4 |
| 75 | South | Songkhla | General Site | 0.2 |
| 76 | South | Surat Thani | General Site | 0.2 |
| 30 | North | Chiang Rai | General Site | 1.9 |
| 31 | North | Chiang Rai | General Site | 3.9 |
| 32 | North | Chiang Mai | General Site | 0.7 |
| 33 | North | Chiang Mai | General Site | 0.9 |
| 34 | North | Nakhon Sawan | General Site | 0.5 |
| 35 | North | Nakhon Sawan | General Site | 5.2 |
| 36 | North | Nan | General Site | 2.1 |
| 37 | North | Nan | General Site | 4.4 |
| 38 | North | Phayao | General Site | 6.4 |
| 39 | North | Phrae | General Site | 0.3 |
| 40 | North | Maehongson | General Site | 5.4 |
| 41 | North | Lampang | General Site | 1.4 |
| 43 | North | Lampang | General Site | 3.8 |
| 44 | North | Lampang | General Site | 6.7 |
| 45 | North | Lampang | General Site | 0.6 |
| 46 | North | Lamphun | General Site | 2.9 |
| | | | **% Average** | **2.1** |

**Table S3:** The $PM_{10}$ data capture **(%)** from each monitoring site for annual average and individual months between 2011 and 2015

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 1 | Central (Bangkok) | General Site | 2011 | 72 | 78 | 95 | 27 | - | - | 96 | 91 | 98 | 98 | 95 | 96 | 92 |
| | | | 2012 | 91 | 58 | 95 | 93 | 88 | 92 | 94 | 94 | 96 | 95 | 97 | 96 | 93 |
| | | | 2013 | 91 | 90 | 90 | 89 | 84 | 91 | 94 | 89 | 93 | 94 | 93 | 93 | 87 |
| | | | 2014 | 75 | 99 | 69 | 84 | 95 | 92 | 92 | 94 | 95 | 63 | 83 | 37 | - |
| | | | 2015 | 71 | - | - | - | 70 | 100 | 100 | 100 | 99 | 99 | 88 | 88 | 98 |
| Site 2 | Central (Bangkok) | General Site | 2011 | 36 | 95 | 74 | 98 | 96 | 65 | 8 | - | - | - | - | - | - |
| | | | 2012 | 23 | - | 63 | 81 | 73 | 62 | - | - | - | - | - | - | - |
| | | | 2013 | 88 | 40 | 96 | 99 | 93 | 97 | 71 | 91 | 96 | 100 | 81 | 97 | 94 |
| | | | 2014 | 95 | 99 | 100 | 95 | 100 | 75 | 100 | 81 | 100 | 97 | 90 | 100 | 100 |
| | | | 2015 | 89 | 99 | 94 | 100 | 68 | 98 | 54 | 98 | 96 | 69 | 98 | 100 | 89 |
| Site 3 | Central | General Site | 2015 | 72 | - | - | - | 68 | 94 | 97 | 99 | 100 | 98 | 100 | 100 | 99 |
| Site 4 | Central (Bangkok) | General Site | 2011 | 28 | 69 | - | 9 | - | - | - | 32 | 57 | 86 | 85 | - | - |
| | | | 2012 | 62 | - | 36 | 27 | - | 9 | 84 | 94 | 100 | 100 | 96 | 98 | 99 |
| | | | 2013 | 81 | 91 | 93 | 60 | 100 | 99 | 90 | 78 | 91 | 73 | 88 | 60 | 49 |
| | | | 2014 | 78 | 29 | 44 | 91 | 93 | 86 | 99 | 88 | 58 | 59 | 85 | 97 | 99 |
| | | | 2015 | 55 | 33 | - | - | - | 17 | 47 | 63 | 99 | 99 | 100 | 100 | 99 |
| Site 5 | Central (Bangkok) | General Site | 2011 | 37 | 100 | 98 | 97 | 76 | 77 | - | - | - | - | - | - | - |
| | | | 2012 | 37 | - | - | - | - | - | - | - | 44 | 100 | 100 | 99 | 95 |
| | | | 2013 | 92 | 99 | 65 | 83 | 99 | 97 | 98 | 98 | 70 | 98 | 99 | 100 | 99 |
| | | | 2014 | 81 | 99 | 86 | 30 | 100 | 100 | 100 | 100 | 90 | 100 | 100 | 71 | - |
| Site 6 | Central | General Site | 2011 | 96 | 100 | 99 | 100 | 100 | 100 | 99 | 99 | 98 | 99 | 99 | 65 | 100 |
| | | | 2012 | 99 | 99 | 100 | 99 | 99 | 99 | 100 | 99 | 100 | 100 | 100 | 100 | 97 |
| | | | 2013 | 50 | 100 | 100 | 100 | 100 | 21 | - | - | - | - | - | 81 | 100 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (Bangkok) | | 2014 | 93 | 97 | 81 | 99 | 92 | 95 | 81 | 100 | 100 | 78 | 98 | 100 | 100 |
| | | | 2015 | 98 | 100 | 97 | 100 | 100 | 100 | 98 | 94 | 99 | 100 | 88 | 99 | 100 |
| Site 7 | Central | General Site | 2011 | 88 | 100 | 100 | 90 | 93 | 96 | 11 | 79 | 99 | 99 | 97 | 100 | 86 |
| | (Bangkok) | | 2012 | 95 | 82 | 90 | 99 | 98 | 96 | 98 | 98 | 98 | 97 | 100 | 100 | 82 |
| | | | 2013 | 95 | 94 | 91 | 100 | 100 | 100 | 100 | 100 | 97 | 100 | 100 | 100 | 58 |
| | | | 2014 | 93 | 93 | 98 | 93 | 91 | 98 | 99 | 100 | 100 | 100 | 98 | 96 | 52 |
| | | | 2015 | 80 | 30 | 38 | 100 | 99 | 96 | 49 | 60 | 98 | 99 | 86 | 100 | 99 |
| Site 8 | Central | General Site | 2011 | 27 | 100 | 100 | 32 | 99 | 4 | - | - | - | - | - | - | - |
| | (Bangkok) | | 2013 | 92 | 40 | 96 | 92 | 97 | 100 | 100 | 97 | 100 | 93 | 100 | 90 | 100 |
| | | | 2014 | 98 | 96 | 100 | 95 | 100 | 97 | 99 | 100 | 97 | 98 | 97 | 100 | 97 |
| | | | 2015 | 86 | 100 | 100 | 72 | 100 | 89 | 100 | 71 | 100 | 100 | 100 | 52 | 56 |
| Site 9 | Central | General Site | 2011 | 68 | 100 | 100 | 100 | 100 | 99 | 100 | 98 | 63 | 47 | 13 | - | - |
| | (Bangkok) | | 2012 | 54 | 19 | - | 57 | 68 | 53 | - | - | 48 | 100 | 99 | 100 | 100 |
| | | | 2013 | 99 | 89 | 100 | 100 | 99 | 99 | 99 | 100 | 100 | 100 | 100 | 100 | 100 |
| | | | 2014 | 81 | 3 | 15 | 100 | 100 | 100 | 67 | 100 | 100 | 100 | 100 | 83 | 97 |
| | | | 2015 | 91 | 100 | 100 | 100 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 98 | - |
| Site 10 | Central | Roadside Site | 2011 | 78 | 81 | 98 | 65 | 64 | 32 | 82 | 97 | 99 | 97 | 91 | 98 | 37 |
| | (Bangkok) | | 2012 | 67 | 81 | 78 | 51 | - | - | 56 | 99 | 94 | 92 | 82 | 83 | 81 |
| | | | 2013 | 61 | 80 | 97 | 67 | 61 | 83 | 70 | 34 | 27 | 59 | 26 | 97 | 35 |
| | | | 2014 | 85 | - | 78 | 83 | 94 | 99 | 87 | 100 | 86 | 99 | 94 | 99 | 99 |
| | | | 2015 | 19 | 96 | 99 | 38 | - | - | - | - | - | - | - | - | - |
| Site 11 | Central | Roadside Site | 2011 | 70 | 88 | 95 | 90 | 43 | 65 | 78 | 74 | 99 | 52 | 98 | 26 | 31 |
| | (Bangkok) | | 2012 | 50 | 43 | 100 | 38 | 31 | 32 | - | - | 22 | 85 | 99 | 74 | 79 |
| | | | 2013 | 71 | 99 | 99 | 95 | 70 | 67 | 32 | 94 | 80 | 91 | 98 | 32 | - |
| | | | 2014 | 72 | - | 28 | 53 | 74 | 67 | 98 | 97 | 86 | 99 | 75 | 99 | 82 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2015 | 69 | 30 | 74 | 96 | 38 | 96 | 75 | 99 | 99 | 84 | 99 | 36 | - |
| Site 12 | Central (Bangkok) | Roadside Site | 2011 | 97 | 100 | 98 | 100 | 100 | 100 | 100 | 100 | 85 | 100 | 89 | 99 | 99 |
| | | | 2012 | 88 | 81 | 100 | 73 | 94 | 45 | 75 | 100 | 100 | 100 | 100 | 93 | 100 |
| | | | 2013 | 93 | 99 | 100 | 100 | 78 | 99 | 89 | 100 | 96 | 76 | 83 | 100 | 99 |
| | | | 2014 | 87 | 50 | 79 | 100 | 85 | 99 | 93 | 100 | 100 | 100 | 98 | 85 | 60 |
| | | | 2015 | 41 | 82 | 98 | 68 | 100 | 74 | 72 | - | - | - | - | - | - |
| Site 13 | Central | Roadside Site | 2012 | 67 | 54 | 77 | - | - | 78 | 76 | 92 | 90 | 92 | 67 | 89 | 92 |
| Site 14 | Central (Bangkok) | Roadside Site | 2011 | 77 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 13 | 2 | 8 |
| | | | 2012 | 75 | 99 | 5 | 73 | 18 | 40 | 100 | 92 | 81 | 91 | 93 | 98 | 100 |
| | | | 2013 | 70 | 99 | 97 | 99 | 91 | 88 | 99 | 56 | 98 | 67 | - | 19 | 36 |
| | | | 2014 | 74 | 14 | 27 | 88 | 98 | 85 | 86 | 100 | 100 | 98 | 78 | 62 | 54 |
| | | | 2015 | 98 | 82 | 100 | 100 | 100 | 100 | 100 | 99 | 100 | 100 | 100 | 100 | 100 |
| Site 15 | Central (Bangkok) | Roadside Site | 2011 | 85 | 100 | 100 | 92 | 64 | 100 | 100 | 87 | 100 | 100 | 57 | 18 | 100 |
| | | | 2012 | 71 | 84 | 97 | 95 | 82 | 14 | - | - | 77 | 100 | 100 | 100 | 100 |
| | | | 2013 | 95 | 100 | 90 | 100 | 100 | 100 | 100 | 100 | 100 | 88 | 99 | 100 | 66 |
| | | | 2014 | 94 | 99 | 99 | 99 | 99 | 79 | 88 | 100 | 88 | 100 | 100 | 98 | 85 |
| | | | 2015 | 58 | 100 | 99 | 100 | 100 | 100 | 100 | 37 | - | - | - | 68 | - |
| Site 16 | Central (Bangkok) | Roadside Site | 2011 | 83 | 37 | 100 | 99 | 100 | 99 | 61 | 50 | 99 | 90 | 72 | 96 | 97 |
| | | | 2012 | 94 | 100 | 91 | 99 | 75 | 98 | 99 | 100 | 69 | 99 | 99 | 97 | 99 |
| | | | 2013 | 98 | 96 | 92 | 100 | 99 | 97 | 100 | 99 | 100 | 99 | 100 | 100 | 97 |
| | | | 2014 | 93 | 40 | 100 | 98 | 99 | 98 | 95 | 100 | 94 | 100 | 100 | 99 | 99 |
| | | | 2015 | 99 | 100 | 99 | 100 | 100 | 100 | 98 | 88 | 100 | 100 | 99 | 100 | 100 |
| Site 17 | Central | General Site | 2011 | 25 | 95 | 41 | 46 | - | - | - | 49 | - | 48 | 23 | - | - |
| | | | 2012 | 63 | - | - | - | - | 72 | 93 | 100 | 91 | 100 | 100 | 100 | 96 |
| | | | 2013 | 87 | 98 | 89 | 89 | 99 | 88 | 77 | 86 | 96 | 83 | 97 | 74 | 70 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (Bangkok) | | 2014 | 51 | 100 | 80 | - | - | - | - | - | 48 | 100 | 94 | 94 | 100 |
| | | | 2015 | 99 | 98 | 100 | 100 | 96 | 100 | 100 | 100 | 99 | 99 | 100 | 100 | 100 |
| Site 18 | Central (Bangkok) | General Site | 2011 | 48 | 99 | 99 | 99 | 97 | 98 | 91 | - | - | - | - | - | - |
| | | | 2012 | 47 | - | - | - | - | - | - | 90 | 83 | 97 | 95 | 100 | 100 |
| | | | 2013 | 95 | 100 | 100 | 100 | 100 | 99 | 100 | 88 | 94 | 77 | 99 | 91 | 99 |
| | | | 2014 | 97 | 99 | 98 | 89 | 99 | 98 | 98 | 98 | 99 | 82 | 100 | 100 | 100 |
| | | | 2015 | 89 | 99 | 92 | 100 | 4 | NA | NA | NA | NA | NA | NA | NA | NA |
| Site 19 | Central | General Site | 2011 | 86 | 100 | 98 | 100 | 99 | 100 | 100 | 100 | 100 | 100 | 40 | 1 | 96 |
| | | | 2012 | 96 | 100 | 100 | 100 | 100 | 99 | 99 | 98 | 82 | 99 | 99 | 100 | 76 |
| | | | 2013 | 91 | 79 | 100 | 100 | 99 | 98 | 98 | 99 | 97 | 52 | 90 | 87 | 99 |
| | | | 2014 | 91 | 76 | 85 | 90 | 94 | 91 | 93 | 94 | 94 | 96 | 97 | 98 | 81 |
| | | | 2015 | 86 | 99 | 98 | 97 | 83 | 42 | 88 | 94 | 54 | 87 | 97 | 96 | 99 |
| Site 20 | Central | General Site | 2011 | 99 | 100 | 99 | 98 | 98 | 99 | 98 | 100 | 100 | 99 | 98 | 100 | 99 |
| | | | 2012 | 85 | 99 | 90 | 97 | 98 | 94 | 97 | 70 | 95 | 93 | 97 | 88 | - |
| | | | 2013 | 91 | 42 | 93 | 100 | 99 | 91 | 96 | 89 | 97 | 93 | 94 | 97 | 100 |
| | | | 2014 | 87 | 99 | 89 | 91 | 100 | 77 | 77 | 71 | 50 | 93 | 96 | 99 | 99 |
| | | | 2015 | 45 | 81 | 100 | 89 | 95 | 61 | 21 | - | - | - | - | - | 92 |
| Site 21 | Central | General Site | 2011 | 75 | 94 | 100 | 86 | 95 | 99 | 99 | 93 | 99 | 98 | 35 | - | - |
| | | | 2012 | 41 | - | - | - | - | - | - | - | 98 | 98 | 98 | 99 | 96 |
| | | | 2013 | 94 | 99 | 94 | 99 | 96 | 94 | 88 | 96 | 95 | 88 | 91 | 100 | 92 |
| | | | 2014 | 94 | 88 | 95 | 94 | 89 | 97 | 98 | 86 | 96 | 96 | 94 | 99 | 94 |
| | | | 2015 | 73 | 93 | 100 | 99 | 68 | 90 | 88 | 64 | 59 | 91 | 96 | 36 | - |
| Site 22 | Central | General Site | 2011 | 86 | 63 | 67 | 96 | 99 | 92 | 92 | 90 | 87 | 99 | 97 | 44 | 100 |
| | | | 2012 | 91 | 86 | 79 | 93 | 99 | 79 | 100 | 99 | 88 | 95 | 89 | 95 | 94 |
| | | | 2013 | 79 | 91 | 79 | 75 | 77 | 68 | 97 | 70 | 29 | 99 | 91 | 72 | 98 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2014 | 72 | 97 | 94 | 48 | 67 | 97 | 100 | 93 | 78 | 99 | 79 | 14 | - |
| Site 23 | Central | General Site | 2011 | 75 | 100 | 38 | 42 | 78 | 100 | 94 | 91 | 93 | 100 | 33 | 31 | 94 |
| | | | 2012 | 91 | 100 | 83 | 87 | 64 | 97 | 100 | 100 | 91 | 84 | 99 | 96 | 88 |
| | | | 2013 | 92 | 85 | 100 | 100 | 83 | 100 | 99 | 100 | 75 | 93 | 80 | 91 | 100 |
| | | | 2014 | 97 | 95 | 100 | 91 | 100 | 90 | 87 | 100 | 100 | 100 | 100 | 100 | 100 |
| | | | 2015 | 84 | 94 | 98 | 92 | 88 | 94 | 77 | 100 | 100 | 95 | 91 | 78 | - |
| Site 24 | Central | General Site | 2011 | 86 | 100 | 99 | 99 | 99 | 98 | 98 | 98 | 95 | 96 | 35 | 19 | 100 |
| | | | 2012 | 98 | 98 | 96 | 95 | 94 | 97 | 98 | 100 | 100 | 100 | 100 | 99 | 99 |
| | | | 2013 | 98 | 90 | 95 | 100 | 100 | 99 | 99 | 99 | 99 | 100 | 100 | 100 | 100 |
| | | | 2014 | 99 | 100 | 100 | 100 | 100 | 95 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | | | 2015 | 100 | 100 | 100 | 100 | 99 | 100 | 100 | 100 | 100 | 99 | 100 | 99 | 100 |
| Site 25 | Central | General Site | 2011 | 85 | 100 | 100 | 100 | 84 | 92 | 90 | 100 | 97 | 100 | 40 | 28 | 91 |
| | | | 2012 | 96 | 84 | 77 | 100 | 100 | 99 | 100 | 100 | 100 | 96 | 100 | 95 | 100 |
| | | | 2013 | 95 | 86 | 100 | 98 | 97 | 99 | 87 | 97 | 94 | 95 | 93 | 99 | 90 |
| | | | 2014 | 93 | 92 | 99 | 99 | 100 | 86 | 99 | 92 | 100 | 100 | 88 | 100 | 64 |
| | | | 2015 | 95 | 100 | 99 | 99 | 100 | 69 | 100 | 96 | 79 | 100 | 100 | 100 | 100 |
| Site 26 | Central | General Site | 2011 | 87 | 100 | 100 | 99 | 98 | 99 | 97 | 95 | 92 | 99 | 40 | 24 | 100 |
| | | | 2012 | 96 | 99 | 99 | 70 | 95 | 99 | 98 | 99 | 98 | 98 | 100 | 99 | 100 |
| | | | 2013 | 96 | 93 | 99 | 87 | 88 | 98 | 99 | 95 | 100 | 99 | 99 | 100 | 100 |
| | | | 2014 | 99 | 100 | 99 | 98 | 100 | 98 | 98 | 99 | 99 | 99 | 100 | 99 | 99 |
| | | | 2015 | 78 | 100 | 98 | 95 | 49 | 78 | 100 | 99 | 99 | 98 | 93 | - | 30 |
| Site 27 | Central | General Site | 2011 | 84 | 96 | 99 | 100 | 98 | 100 | 99 | 100 | 97 | 97 | 73 | - | 49 |
| | | | 2012 | 51 | 98 | 100 | 99 | 98 | 98 | 99 | 27 | - | - | - | - | - |
| | | | 2013 | 89 | 42 | 100 | 91 | 79 | 91 | 98 | 95 | 90 | 93 | 97 | 97 | 98 |
| | | | 2014 | 93 | 85 | 100 | 96 | 100 | 80 | 84 | 99 | 86 | 95 | 94 | 100 | 100 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2015 | 82 | 100 | 100 | 80 | 100 | 100 | 97 | 76 | 62 | 84 | 77 | 76 | 33 |
| Site 28 | Central | General Site | 2013 | 99 | NA | NA | NA | NA | NA | NA | NA | NA | NA | 99 | 100 | 99 |
| | | | 2014 | 97 | 99 | 100 | 96 | 96 | 100 | 96 | 99 | 100 | 96 | 100 | 88 | 99 |
| | | | 2015 | 91 | 98 | 87 | 100 | 95 | 100 | 100 | 93 | 100 | 99 | 96 | 92 | 36 |
| Site 29 | Central | General Site | 2011 | 90 | 99 | 99 | 99 | 99 | 97 | 97 | 95 | 96 | 94 | 80 | 21 | 100 |
| | | | 2012 | 85 | 99 | 99 | 98 | 99 | 99 | 99 | 100 | 100 | 32 | 36 | 63 | 96 |
| | | | 2013 | 61 | 100 | 98 | 31 | 99 | 100 | 100 | 27 | - | - | NA | NA | NA |
| Site 30 | North | General Site | 2011 | 99 | 100 | 100 | 100 | 99 | 100 | 100 | 99 | 98 | 99 | 88 | 100 | 100 |
| | | | 2012 | 98 | 100 | 100 | 99 | 100 | 99 | 99 | 80 | 99 | 99 | 99 | 99 | 100 |
| | | | 2013 | 94 | 99 | 95 | 98 | 100 | 61 | 98 | 99 | 100 | 91 | 87 | 98 | 99 |
| | | | 2014 | 96 | 100 | 99 | 96 | 90 | 93 | 99 | 92 | 94 | 96 | 100 | 98 | 90 |
| | | | 2015 | 91 | 100 | 100 | 99 | 98 | 95 | 99 | 97 | 97 | 80 | 65 | 69 | 97 |
| Site 31 | North | General Site | 2011 | 43 | - | - | - | - | - | - | 40 | 91 | 98 | 96 | 95 | 97 |
| | | | 2012 | 81 | 99 | 100 | 98 | 98 | 95 | 85 | 79 | 84 | 55 | - | 90 | 96 |
| | | | 2013 | 85 | 81 | 78 | 81 | 91 | 100 | 95 | 27 | 75 | 95 | 100 | 98 | 99 |
| | | | 2014 | 92 | 100 | 100 | 100 | 100 | 85 | 84 | 88 | 79 | 84 | 95 | 96 | 96 |
| | | | 2015 | 68 | 89 | 100 | 99 | 98 | 93 | 46 | 24 | - | 4 | 65 | 100 | 99 |
| Site 32 | North | General Site | 2011 | 95 | 95 | 91 | 94 | 84 | 99 | 100 | 81 | 95 | 100 | 100 | 100 | 100 |
| | | | 2012 | 96 | 99 | 83 | 92 | 86 | 99 | 99 | 100 | 100 | 100 | 90 | 100 | 99 |
| | | | 2013 | 99 | 100 | 93 | 99 | 98 | 99 | 100 | 100 | 100 | 99 | 100 | 100 | 100 |
| | | | 2014 | 98 | 100 | 99 | 97 | 91 | 100 | 100 | 100 | 99 | 100 | 100 | 100 | 92 |
| | | | 2015 | 99 | 100 | 100 | 100 | 100 | 99 | 99 | 97 | 100 | 100 | 100 | 100 | 96 |
| Site 33 | North | General Site | 2011 | 97 | 100 | 100 | 99 | 98 | 86 | 99 | 100 | 100 | 100 | 100 | 83 | 100 |
| | | | 2012 | 95 | 100 | 100 | 99 | 100 | 67 | 100 | 99 | 99 | 99 | 100 | 89 | 93 |
| | | | 2013 | 98 | 98 | 100 | 98 | 93 | 99 | 98 | 100 | 99 | 99 | 99 | 100 | 86 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2014 | 92 | 100 | 100 | 96 | 98 | 98 | 99 | 92 | 38 | 90 | 97 | 100 | 100 |
| | | | 2015 | 98 | 100 | 100 | 100 | 98 | 97 | 93 | 99 | 97 | 100 | 99 | 99 | 98 |
| Site 34 | North | General Site | 2013 | 91 | 42 | 95 | 96 | 99 | 99 | 96 | 99 | 90 | 81 | 98 | 96 | 98 |
| | | | 2014 | 96 | 99 | 99 | 92 | 97 | 93 | 99 | 91 | 99 | 99 | 100 | 93 | 92 |
| | | | 2015 | 91 | 99 | 99 | 100 | 99 | 81 | 95 | 97 | 94 | 71 | 99 | 54 | 100 |
| Site 35 | North | General Site | 2011 | 79 | 76 | 100 | 54 | 99 | 98 | 97 | 93 | 99 | 98 | 34 | 3 | 100 |
| | | | 2012 | 85 | 93 | 90 | 95 | 90 | 90 | 91 | 92 | 97 | 96 | 96 | 93 | - |
| Site 36 | North | General Site | 2011 | 96 | 100 | 100 | 100 | 55 | 99 | 99 | 99 | 99 | 99 | 99 | 100 | 99 |
| | | | 2012 | 99 | 100 | 99 | 100 | 100 | 99 | 99 | 98 | 99 | 99 | 99 | 100 | 100 |
| | | | 2013 | 90 | 100 | 78 | 97 | 98 | 98 | 99 | 99 | 93 | 89 | 94 | 100 | 35 |
| | | | 2014 | 95 | 54 | 96 | 100 | 99 | 100 | 100 | 99 | 98 | 99 | 99 | 100 | 99 |
| | | | 2015 | 98 | 99 | 99 | 99 | 100 | 100 | 88 | 100 | 99 | 98 | 100 | 99 | 99 |
| Site 37 | North | General Site | 2015 | 98 | NA | NA | NA | NA | NA | 100 | 97 | 98 | 99 | 99 | 99 | 98 |
| Site 38 | North | General Site | 2011 | 92 | 95 | 90 | 87 | 96 | 75 | 95 | 99 | 76 | 89 | 100 | 100 | 100 |
| | | | 2012 | 78 | 100 | 100 | 91 | 75 | 100 | 93 | 100 | 82 | - | 61 | 72 | 64 |
| | | | 2013 | 91 | 97 | 94 | 98 | 89 | 100 | 91 | 98 | 100 | 41 | 90 | 90 | 98 |
| | | | 2014 | 96 | 100 | 86 | 100 | 99 | 98 | 85 | 97 | 100 | 100 | 100 | 100 | 86 |
| | | | 2015 | 98 | 100 | 100 | 99 | 100 | 100 | 100 | 100 | 85 | 98 | 100 | 100 | 94 |
| Site 39 | North | General Site | 2011 | 95 | 89 | 99 | 85 | 93 | 100 | 100 | 99 | 93 | 91 | 99 | 96 | 98 |
| | | | 2012 | 77 | 98 | 92 | 95 | 86 | 94 | 73 | 45 | 43 | 62 | 42 | 100 | 98 |
| | | | 2013 | 99 | 94 | 98 | 100 | 100 | 100 | 100 | 96 | 100 | 100 | 100 | 95 | 100 |
| | | | 2014 | 91 | 59 | 99 | 98 | 99 | 98 | 88 | 79 | 98 | 100 | 100 | 100 | 76 |
| | | | 2015 | 88 | 86 | 97 | 98 | 99 | 99 | 92 | 100 | 89 | 100 | 100 | 67 | 29 |
| Site 40 | North | General Site | 2011 | 99 | 100 | 100 | 100 | 98 | 99 | 99 | 98 | 97 | 97 | 99 | 99 | 100 |
| | | | 2012 | 94 | 100 | 100 | 98 | 72 | 81 | 97 | 97 | 94 | 94 | 98 | 93 | 99 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2013 | 89 | 99 | 99 | 95 | 90 | 77 | 92 | 94 | 82 | 69 | 82 | 97 | 99 |
| | | | 2014 | 98 | 100 | 96 | 99 | 95 | 99 | 96 | 98 | 99 | 96 | 95 | 96 | 100 |
| | | | 2015 | 72 | 100 | 95 | 95 | 96 | 81 | 95 | 68 | 87 | - | 13 | 93 | 42 |
| Site 41 | North | General Site | 2013 | 91 | 38 | 95 | 96 | 89 | 97 | 97 | 100 | 99 | 94 | 100 | 95 | 98 |
| | | | 2014 | 93 | 99 | 99 | 99 | 90 | 79 | 97 | 97 | 98 | 97 | 91 | 78 | 97 |
| | | | 2015 | 96 | 97 | 100 | 97 | 97 | 96 | 97 | 96 | 81 | 99 | 100 | 100 | 99 |
| Site 43 | North | General Site | 2011 | 85 | 99 | 90 | 95 | 90 | 75 | 8 | 77 | 99 | 98 | 95 | 98 | 99 |
| | | | 2012 | 91 | 99 | 88 | 95 | 78 | 93 | 90 | 88 | 92 | 91 | 93 | 90 | 93 |
| | | | 2013 | 80 | 92 | 93 | 94 | 94 | 50 | 88 | 81 | 78 | 75 | 70 | 83 | 65 |
| | | | 2014 | 93 | 94 | 99 | 93 | 83 | 95 | 95 | 93 | 93 | 83 | 94 | 97 | 98 |
| | | | 2015 | 90 | 98 | 94 | 97 | 96 | 91 | 91 | 94 | 92 | 43 | 96 | 98 | 91 |
| Site 44 | North | General Site | 2011 | 87 | 99 | 35 | 81 | 98 | 95 | 93 | 92 | 90 | 92 | 83 | 97 | 91 |
| | | | 2012 | 83 | 82 | 100 | 91 | 98 | 99 | 99 | 99 | 55 | 5 | 80 | 96 | 92 |
| | | | 2013 | 86 | 98 | 75 | 100 | 94 | 86 | 20 | 91 | 91 | 87 | 97 | 94 | 98 |
| | | | 2014 | 49 | 68 | - | - | - | - | - | 23 | 99 | 97 | 100 | 99 | 100 |
| | | | 2015 | 98 | 100 | 100 | 100 | 100 | 96 | 98 | 99 | 94 | 97 | 96 | 98 | 96 |
| Site 45 | North | General Site | 2011 | 89 | 85 | 43 | 100 | 99 | 97 | 89 | 75 | 97 | 89 | 98 | 94 | 96 |
| | | | 2012 | 94 | 95 | 99 | 100 | 98 | 99 | 99 | 90 | 93 | 72 | 96 | 85 | 98 |
| | | | 2013 | 54 | 98 | 99 | 91 | 99 | 84 | 24 | - | - | - | - | 76 | 85 |
| | | | 2014 | 94 | 97 | 90 | 96 | 97 | 98 | 97 | 99 | 87 | 80 | 98 | 96 | 97 |
| | | | 2015 | 93 | 84 | 99 | 98 | 85 | 71 | 96 | 99 | 99 | 98 | 92 | 96 | 97 |
| Site 46 | North | General Site | 2011 | 99 | 99 | 100 | 100 | 100 | 99 | 99 | 98 | 99 | 99 | 98 | 100 | 99 |
| | | | 2012 | 97 | 100 | 100 | 100 | 100 | 99 | 99 | 96 | 98 | 97 | 94 | 84 | 100 |
| | | | 2013 | 98 | 100 | 100 | 98 | 100 | 98 | 95 | 97 | 98 | 98 | 99 | 100 | 100 |
| | | | 2014 | 99 | 100 | 93 | 100 | 98 | 99 | 99 | 99 | 99 | 98 | 98 | 100 | 100 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2015 | 87 | 100 | 98 | 99 | 98 | 99 | 95 | 98 | 56 | - | 97 | 100 | 99 |
| Site 47 | Central | General Site | 2014 | 99 | NA | NA | NA | NA | NA | NA | NA | 95 | 100 | 100 | 99 | 99 |
| | | | 2015 | 96 | 82 | 100 | 97 | 99 | 100 | 99 | 96 | 99 | 99 | 89 | 98 | 98 |
| Site 48 | Central | General Site | 2011 | 95 | 95 | 74 | 100 | 99 | 98 | 96 | 96 | 92 | 90 | 93 | 100 | 100 |
| | | | 2012 | 90 | 97 | 98 | 97 | 98 | 94 | 84 | 94 | 74 | 51 | 99 | 99 | 100 |
| | | | 2013 | 79 | 83 | 99 | 98 | 96 | 97 | 61 | 70 | 49 | 97 | 46 | 60 | 100 |
| | | | 2014 | 63 | 100 | 58 | 45 | 99 | 53 | 100 | 33 | - | NA | NA | NA | NA |
| Site 49 | Central | General Site | 2011 | 95 | 100 | 100 | 79 | 99 | 100 | 99 | 93 | 77 | 99 | 100 | 100 | 100 |
| | | | 2012 | 98 | 100 | 99 | 99 | 88 | 99 | 99 | 100 | 100 | 100 | 99 | 99 | 100 |
| | | | 2013 | 94 | 100 | 56 | 99 | 100 | 100 | 99 | 96 | 100 | 99 | 99 | 83 | 100 |
| | | | 2014 | 98 | 100 | 100 | 95 | 95 | 99 | 99 | 97 | 89 | 100 | 100 | 100 | 99 |
| | | | 2015 | 96 | 99 | 98 | 97 | 100 | 100 | 84 | 100 | 94 | 97 | 97 | 96 | 94 |
| Site 50 | Central | General Site | 2011 | 85 | 87 | 54 | 47 | 78 | 84 | 87 | 83 | 100 | 100 | 99 | 100 | 99 |
| | | | 2012 | 89 | 100 | 93 | 100 | 77 | 11 | 92 | 98 | 94 | 100 | 100 | 100 | 100 |
| | | | 2013 | 96 | 62 | 100 | 100 | 100 | 100 | 100 | 97 | 100 | 100 | 100 | 100 | 100 |
| | | | 2014 | 93 | 100 | 100 | 100 | 82 | 98 | 96 | 100 | 100 | 100 | 100 | 75 | 62 |
| | | | 2015 | 95 | 100 | 99 | 88 | 71 | 99 | 93 | 100 | 100 | 100 | 100 | 100 | 95 |
| Site 51 | Central | General Site | 2011 | 76 | 100 | 100 | 100 | 99 | 100 | 98 | 97 | 98 | 97 | 23 | - | - |
| | | | 2013 | 93 | 42 | 98 | 100 | 97 | 99 | 99 | 88 | 99 | 100 | 100 | 96 | 95 |
| | | | 2014 | 98 | 99 | 100 | 100 | 97 | 97 | 91 | 98 | 99 | 98 | 100 | 96 | 98 |
| | | | 2015 | 87 | 98 | 100 | 96 | 100 | 99 | 68 | 33 | 98 | 91 | 99 | 59 | 99 |
| Site 52 | East | General Site | 2014 | 100 | NA | NA | NA | NA | NA | NA | NA | NA | 99 | 100 | 100 | 100 |
| | | | 2015 | 95 | 100 | 100 | 100 | 100 | 98 | 85 | 97 | 92 | 95 | 100 | 86 | 90 |
| Site 53 | East | General Site | 2011 | 93 | 100 | 99 | 99 | 96 | 62 | 89 | 94 | 94 | 88 | 92 | 99 | 100 |
| | | | 2012 | 89 | 98 | 99 | 98 | 88 | 90 | 100 | 96 | 90 | 91 | 68 | 51 | 96 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2013 | 78 | 97 | 97 | 94 | 83 | 91 | 58 | 80 | 36 | 90 | 99 | 59 | 55 |
| | | | 2014 | 89 | 100 | 75 | 96 | 100 | 98 | 98 | 98 | 59 | - | NA | NA | NA |
| Site 54 | East | General Site | 2011 | 87 | 75 | 41 | 97 | 100 | 100 | 99 | 94 | 90 | 97 | 64 | 86 | 99 |
| | | | 2012 | 84 | 75 | 26 | 95 | 94 | 100 | 88 | 98 | 98 | 97 | 74 | 84 | 80 |
| | | | 2013 | 71 | 82 | 60 | 35 | 7 | 85 | 34 | 91 | 100 | 100 | 100 | 100 | 51 |
| | | | 2014 | 79 | 35 | 88 | 92 | 99 | 100 | 86 | 99 | 100 | 98 | 91 | 59 | 2 |
| | | | 2015 | 70 | - | - | - | 71 | 94 | 91 | 100 | 99 | 93 | 97 | 98 | 96 |
| Site 55 | East | General Site | 2013 | 98 | NA | NA | NA | NA | NA | NA | NA | NA | 100 | 98 | 99 | 97 |
| | | | 2014 | 98 | 93 | 95 | 98 | 99 | 99 | 98 | 99 | 97 | 100 | 100 | 100 | 100 |
| | | | 2015 | 99 | 98 | 99 | 99 | 99 | 97 | 100 | 99 | 99 | 100 | 100 | 94 | 99 |
| Site 56 | East | General Site | 2011 | 92 | 98 | 100 | 54 | 99 | 92 | 98 | 90 | 96 | 90 | 99 | 100 | 91 |
| | | | 2012 | 91 | 84 | 61 | 91 | 84 | 88 | 95 | 98 | 98 | 97 | 97 | 98 | 97 |
| | | | 2013 | 82 | 97 | 97 | 97 | 78 | 95 | 95 | 88 | 91 | - | NA | NA | NA |
| Site 57 | East | General Site | 2015 | 96 | NA | NA | NA | 70 | 100 | 99 | 100 | 99 | 98 | 100 | 100 | 99 |
| Site 58 | East | General Site | 2011 | 94 | 100 | 92 | 66 | 100 | 100 | 98 | 100 | 100 | 98 | 89 | 98 | 93 |
| | | | 2012 | 93 | 100 | 100 | 64 | 100 | 100 | 98 | 99 | 99 | 97 | 99 | 83 | 81 |
| | | | 2013 | 78 | 95 | 72 | 81 | 96 | 100 | 96 | 92 | 97 | 82 | 45 | 61 | 26 |
| | | | 2014 | 79 | 12 | 30 | 81 | 84 | 78 | 84 | 88 | 99 | 100 | 97 | 94 | 99 |
| | | | 2015 | 71 | 100 | 100 | 39 | - | NA | NA | NA | NA | NA | NA | NA | NA |
| Site 59 | East | General Site | 2014 | 100 | NA | NA | NA | NA | NA | NA | 100 | 100 | 100 | 100 | 100 | 100 |
| | | | 2015 | 99 | 100 | 100 | 100 | 100 | 96 | 100 | 94 | 96 | 98 | 100 | 100 | 100 |
| Site 60 | East | General Site | 2011 | 94 | 88 | 100 | 99 | 89 | 81 | 79 | 97 | 97 | 98 | 99 | 99 | 100 |
| | | | 2012 | 81 | 46 | 55 | 42 | 71 | 82 | 99 | 98 | 99 | 100 | 93 | 91 | 98 |
| | | | 2013 | 85 | 79 | 86 | 76 | 98 | 94 | 92 | 97 | 99 | 98 | 95 | 69 | 43 |
| | | | 2014 | 72 | 92 | 97 | 63 | 72 | 47 | 68 | 67 | NA | NA | NA | NA | NA |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 61 | East | General Site | 2011 | 88 | 100 | 100 | 100 | 100 | 74 | 89 | 96 | 90 | 93 | 80 | 83 | 55 |
| | | | 2012 | 88 | 99 | 89 | 82 | 93 | 100 | 100 | 86 | 69 | 82 | 75 | 96 | 80 |
| | | | 2013 | 74 | 76 | 90 | 100 | 76 | 91 | 85 | 70 | 83 | 46 | 87 | 47 | 41 |
| | | | 2014 | 97 | 100 | 99 | 99 | 92 | 99 | 89 | 100 | 99 | 97 | 100 | 100 | 84 |
| | | | 2015 | 96 | 100 | 96 | 99 | 100 | 96 | 97 | 100 | 100 | 99 | 96 | 92 | 72 |
| Site 62 | East | General Site | 2011 | 43 | - | - | - | - | - | - | 72 | 100 | 95 | 98 | 94 | 56 |
| | | | 2012 | 97 | 78 | 99 | 100 | 98 | 100 | 99 | 98 | 99 | 99 | 99 | 97 | 98 |
| | | | 2013 | 95 | 100 | 91 | 99 | 99 | 99 | 97 | 99 | 98 | 100 | 100 | 99 | 65 |
| | | | 2014 | 90 | 5 | 100 | 100 | 97 | 94 | 100 | 100 | 97 | 99 | 96 | 99 | 100 |
| | | | 2015 | 87 | 98 | 100 | 98 | 98 | 97 | 98 | 93 | 92 | 80 | 92 | 72 | 23 |
| Site 64 | East | General Site | 2011 | 75 | 49 | 58 | 78 | 93 | 71 | 75 | 46 | 91 | 98 | 62 | 100 | 80 |
| | | | 2012 | 89 | 99 | 68 | 100 | 79 | 92 | 92 | 100 | 100 | 78 | 72 | 86 | 100 |
| | | | 2013 | 87 | 80 | 100 | 97 | 94 | 76 | 72 | 92 | 77 | 68 | 96 | 92 | 99 |
| | | | 2014 | 88 | 100 | 80 | 58 | 60 | 86 | 81 | 100 | 98 | 99 | 97 | 100 | 99 |
| | | | 2015 | 86 | 99 | 99 | 100 | 84 | 95 | 81 | 92 | 97 | 92 | 98 | 81 | 15 |
| Site 65 | East | General Site | 2011 | 15 | - | - | - | - | - | - | - | - | - | - | 76 | 100 |
| | | | 2012 | 98 | 99 | 97 | 99 | 99 | 94 | 93 | 99 | 98 | 99 | 99 | 99 | 99 |
| | | | 2013 | 98 | 99 | 99 | 95 | 97 | 99 | 99 | 99 | 98 | 96 | 98 | 98 | 99 |
| | | | 2014 | 94 | 98 | 99 | 98 | 92 | 94 | 96 | 97 | 98 | 96 | 82 | 95 | 80 |
| | | | 2015 | 86 | 99 | 90 | 97 | 94 | 92 | 88 | 93 | 89 | 68 | 63 | 57 | 96 |
| Site 66 | East | General Site | 2011 | 42 | - | - | - | - | - | 9 | 60 | 76 | 72 | 88 | 99 | 100 |
| | | | 2012 | 80 | 65 | 84 | 97 | 77 | 61 | 44 | 85 | 83 | 72 | 95 | 99 | 99 |
| | | | 2013 | 84 | 95 | 99 | 48 | 25 | 82 | 77 | 94 | 96 | 96 | 99 | 100 | 100 |
| | | | 2014 | 98 | 91 | 91 | 100 | 99 | 100 | 99 | 99 | 99 | 100 | 100 | 100 | 100 |
| | | | 2015 | 97 | 100 | 100 | 100 | 100 | 99 | 100 | 100 | 98 | 95 | 94 | 99 | 78 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 67 | Northeast | General Site | 2013 | 89 | NA | NA | NA | NA | NA | NA | NA | NA | NA | 96 | 95 | 77 |
| | | | 2014 | 93 | 89 | 100 | 100 | 81 | 100 | 99 | 100 | 100 | 100 | 51 | 99 | 100 |
| | | | 2015 | 95 | 100 | 100 | 99 | 100 | 100 | 99 | 100 | 95 | 95 | 93 | 93 | 66 |
| Site 68 | Northeast | General Site | 2011 | 86 | 88 | 31 | 99 | 44 | 99 | 100 | 99 | 99 | 91 | 76 | 100 | 100 |
| | | | 2012 | 91 | 81 | 100 | 100 | 83 | 94 | 99 | 99 | 99 | 97 | 77 | 59 | 100 |
| | | | 2013 | 78 | 98 | 100 | 99 | 67 | 25 | 97 | 93 | 34 | 88 | NA | NA | NA |
| Site 69 | Northeast | General Site | 2011 | 97 | 93 | 100 | 100 | 99 | 77 | 100 | 100 | 100 | 100 | 100 | 100 | 99 |
| | | | 2012 | 98 | 99 | 98 | 99 | 100 | 99 | 96 | 85 | 99 | 100 | 100 | 100 | 100 |
| | | | 2013 | 62 | 100 | 100 | 100 | 21 | 28 | 94 | 47 | 30 | 40 | 28 | 82 | 72 |
| | | | 2014 | 89 | 69 | 100 | 100 | 99 | 100 | 99 | 92 | 100 | 99 | 100 | 100 | 17 |
| | | | 2015 | 81 | 34 | 81 | 20 | 73 | 99 | 99 | 99 | 66 | 99 | 100 | 100 | 100 |
| Site 71 | Northeast | General Site | 2011 | 39 | - | - | - | - | - | - | 53 | 87 | 35 | 86 | 99 | 100 |
| | | | 2012 | 74 | 75 | 96 | 78 | 99 | 99 | 48 | 61 | 88 | 88 | 96 | 55 | 1 |
| | | | 2013 | 66 | 100 | 67 | 6 | 83 | 64 | 52 | 85 | 88 | 35 | 89 | 98 | 27 |
| | | | 2014 | 52 | - | - | 31 | 29 | - | 53 | 99 | 99 | 90 | 81 | 31 | 99 |
| | | | 2015 | 88 | 80 | 57 | 21 | 99 | 100 | 99 | 100 | 99 | 100 | 100 | 100 | 100 |
| Site 72 | South | General Site | 2011 | 86 | 82 | 100 | 99 | 52 | 71 | 79 | 99 | 100 | 81 | 98 | 67 | 100 |
| | | | 2012 | 87 | 82 | 96 | 89 | 84 | 76 | 83 | 98 | 99 | 46 | 100 | 100 | 92 |
| | | | 2013 | 92 | 100 | 82 | 95 | 71 | 98 | 100 | 99 | 85 | 100 | 83 | 99 | 92 |
| | | | 2014 | 94 | 56 | 98 | 98 | 96 | 98 | 96 | 98 | 99 | 98 | 99 | 99 | 97 |
| | | | 2015 | 99 | 99 | 100 | 100 | 99 | 99 | 99 | 99 | 99 | 98 | 99 | 98 | 98 |
| Site 73 | South | General Site | 2011 | 86 | 100 | 79 | 52 | 99 | 94 | 100 | 98 | 97 | 98 | 84 | 98 | 39 |
| | | | 2012 | 92 | 96 | 70 | 72 | 99 | 99 | 99 | 98 | 93 | 81 | 99 | 96 | 99 |
| | | | 2013 | 96 | 96 | 99 | 83 | 95 | 99 | 99 | 100 | 100 | 99 | 98 | 91 | 90 |
| | | | 2014 | 90 | 46 | 87 | 100 | 100 | 99 | 100 | 99 | 97 | 87 | 94 | 89 | 84 |

| Site | Region | Category | Year | Annual Average | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2015 | 72 | 98 | 74 | 66 | 47 | 96 | 13 | 70 | 98 | 94 | 97 | 57 | 51 |
| Site 74 | South | General Site | 2011 | 81 | 61 | 44 | 74 | 78 | 95 | 91 | 88 | 64 | 89 | 97 | 100 | 85 |
| | | | 2012 | 81 | 79 | 47 | 31 | 85 | 96 | 100 | 89 | 97 | 86 | 97 | 90 | 77 |
| | | | 2013 | 91 | 84 | 92 | 100 | 82 | 99 | 90 | 89 | 100 | 96 | 100 | 99 | 67 |
| | | | 2014 | 80 | - | 48 | 86 | 98 | 100 | 85 | 99 | 96 | 87 | 58 | 99 | 99 |
| | | | 2015 | 94 | 100 | 93 | 100 | 91 | 91 | 100 | 90 | 99 | 97 | 96 | 97 | 71 |
| Site 75 | South | General Site | 2011 | 88 | 69 | 70 | 83 | 100 | 99 | 100 | 100 | 93 | 94 | 83 | 71 | 92 |
| | | | 2012 | 93 | 97 | 70 | 69 | 100 | 98 | 99 | 97 | 99 | 98 | 96 | 90 | 98 |
| | | | 2013 | 88 | 89 | 97 | 28 | 94 | 100 | 97 | 100 | 89 | 93 | 95 | 97 | 73 |
| | | | 2014 | 94 | 81 | 97 | 99 | 80 | 100 | 100 | 100 | 97 | 99 | 96 | 75 | 100 |
| | | | 2015 | 78 | 91 | 99 | 91 | 40 | 7 | 93 | 98 | 75 | 99 | 97 | 84 | 66 |
| Site 76 | South | General Site | 2013 | 88 | 42 | 99 | 85 | 100 | 96 | 97 | 89 | 80 | 100 | 87 | 100 | 90 |
| | | | 2014 | 89 | 100 | 100 | 100 | 99 | 98 | 97 | 70 | 43 | 83 | 97 | 78 | 99 |
| | | | 2015 | 62 | 66 | 100 | 67 | 69 | 25 | 82 | 84 | 36 | 100 | 96 | - | 25 |

**Table S4:** The $PM_{10}$ data capture **(%)** from each monitoring site for annual average and each hour between 2011 and 2015

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 1 | Central (Bangkok) | General Site | 2011 | 72 | 70 | 72 | 71 | 71 | 73 | 74 | 73 | 74 | 71 | 71 | 71 | 70 | 69 | 71 | 70 | 72 | 73 | 73 | 72 | 73 | 73 | 73 | 73 | 73 |
| | | | 2012 | 91 | 92 | 92 | 91 | 90 | 92 | 93 | 95 | 93 | 89 | 85 | 87 | 88 | 89 | 89 | 88 | 88 | 89 | 91 | 93 | 92 | 94 | 94 | 92 | 95 |
| | | | 2013 | 91 | 90 | 94 | 88 | 90 | 93 | 96 | 92 | 91 | 92 | 74 | 82 | 90 | 91 | 92 | 88 | 89 | 93 | 92 | 92 | 93 | 91 | 95 | 93 | 93 |
| | | | 2014 | 75 | 74 | 77 | 78 | 77 | 78 | 76 | 75 | 73 | 74 | 69 | 74 | 74 | 74 | 77 | 77 | 73 | 73 | 77 | 74 | 76 | 77 | 72 | 78 | 78 |
| | | | 2015 | 71 | 72 | 72 | 73 | 73 | 73 | 73 | 73 | 73 | 72 | 60 | 60 | 65 | 70 | 71 | 71 | 71 | 71 | 71 | 72 | 72 | 73 | 72 | 71 | 72 |
| Site 2 | Central (Bangkok) | General Site | 2011 | 36 | 36 | 37 | 37 | 36 | 36 | 37 | 36 | 36 | 35 | 35 | 35 | 35 | 36 | 36 | 36 | 36 | 35 | 35 | 36 | 36 | 36 | 36 | 36 | 36 |
| | | | 2012 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 22 | 22 | 22 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 |
| | | | 2013 | 88 | 88 | 87 | 88 | 87 | 87 | 87 | 87 | 87 | 87 | 88 | 87 | 88 | 88 | 88 | 88 | 87 | 87 | 87 | 88 | 88 | 88 | 89 | 88 | 88 |
| | | | 2014 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 94 | 95 | 95 | 94 | 95 | 95 | 95 | 95 | 95 | 95 |
| | | | 2015 | 89 | 90 | 89 | 89 | 88 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 90 | 88 | 87 | 86 | 88 | 89 | 90 | 90 | 90 | 90 | 90 | 90 |
| Site 3 | Central (Bangkok) | General Site | 2015 | 72 | 72 | 72 | 72 | 71 | 70 | 71 | 72 | 72 | 72 | 72 | 70 | 71 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| Site 4 | Central (Bangkok) | General Site | 2011 | 28 | 28 | 29 | 28 | 28 | 28 | 26 | 24 | 25 | 29 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 29 | 28 | 28 | 28 | 28 | 28 | 28 |
| | | | 2012 | 62 | 62 | 61 | 62 | 62 | 62 | 62 | 62 | 61 | 62 | 62 | 61 | 61 | 61 | 61 | 62 | 62 | 62 | 62 | 62 | 62 | 62 | 62 | 62 | 62 |
| | | | 2013 | 81 | 81 | 80 | 80 | 80 | 81 | 82 | 82 | 81 | 81 | 81 | 81 | 82 | 81 | 80 | 82 | 81 | 82 | 82 | 81 | 81 | 81 | 80 | 79 | 80 |
| | | | 2014 | 78 | 78 | 76 | 77 | 78 | 79 | 78 | 79 | 79 | 78 | 76 | 76 | 74 | 75 | 76 | 76 | 78 | 78 | 78 | 78 | 79 | 79 | 79 | 79 | 78 |
| | | | 2015 | 55 | 56 | 56 | 55 | 55 | 55 | 56 | 56 | 55 | 53 | 53 | 55 | 55 | 55 | 56 | 55 | 55 | 55 | 56 | 56 | 56 | 56 | 56 | 56 | 56 |
| Site 5 | Central (Bangkok) | General Site | 2011 | 37 | 37 | 36 | 37 | 38 | 38 | 37 | 38 | 38 | 37 | 38 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 36 | 36 | 36 | 36 |
| | | | 2012 | 37 | 37 | 37 | 36 | 37 | 37 | 37 | 36 | 37 | 37 | 36 | 36 | 37 | 36 | 36 | 37 | 36 | 36 | 37 | 37 | 37 | 37 | 37 | 37 | 37 |
| | | | 2013 | 92 | 92 | 92 | 92 | 92 | 93 | 93 | 92 | 93 | 93 | 93 | 93 | 93 | 93 | 92 | 93 | 92 | 91 | 92 | 91 | 92 | 93 | 93 | 93 | 92 |
| | | | 2014 | 81 | 81 | 82 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 |
| Site 6 | | | 2011 | 96 | 97 | 97 | 97 | 96 | 96 | 97 | 97 | 96 | 95 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 96 | 97 | 96 | 97 | 97 | 97 | 97 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Central (Bangkok) | General Site | 2012 | 99 | 99 | 99 | 99 | 99 | 100 | 100 | 100 | 99 | 100 | 99 | 99 | 98 | 98 | 98 | 99 | 99 | 99 | 100 | 99 | 100 | 99 | 99 | 99 | 100 |
| | | | 2013 | 50 | 50 | 50 | 49 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 49 | 49 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | | | 2014 | 93 | 94 | 94 | 93 | 93 | 94 | 94 | 93 | 93 | 93 | 93 | 93 | 93 | 92 | 93 | 93 | 94 | 94 | 94 | 94 | 94 | 94 | 94 | 94 | 94 |
| | | | 2015 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 97 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 99 | 98 |
| Site 7 | Central (Bangkok) | General Site | 2011 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 87 | 88 | 88 | 86 | 85 | 87 | 87 | 87 | 86 | 86 |
| | | | 2012 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 94 | 94 | 94 | 94 | 94 | 95 | 95 | 96 | 95 | 95 | 95 | 96 | 95 | 96 | 96 |
| | | | 2013 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 96 | 95 | 96 | 96 | 96 | 96 | 95 | 94 | 95 | 94 | 94 | 95 | 95 | 95 | 95 | 95 |
| | | | 2014 | 93 | 91 | 91 | 92 | 92 | 94 | 93 | 93 | 93 | 92 | 93 | 92 | 92 | 93 | 93 | 93 | 93 | 93 | 94 | 94 | 95 | 95 | 94 | 93 | 92 |
| | | | 2015 | 80 | 80 | 78 | 77 | 77 | 79 | 79 | 79 | 80 | 81 | 79 | 79 | 78 | 78 | 79 | 80 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 80 |
| Site 8 | Central (Bangkok) | General Site | 2011 | 27 | 27 | 28 | 28 | 28 | 28 | 28 | 27 | 28 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 |
| | | | 2013 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 91 | 91 | 92 | 92 | 92 | 92 | 92 | 93 | 92 | 92 | 92 | 92 | 92 | 92 |
| | | | 2014 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 |
| | | | 2015 | 86 | 87 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 85 | 86 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 87 |
| Site 9 | Central (Bangkok) | General Site | 2011 | 68 | 69 | 69 | 68 | 69 | 68 | 68 | 69 | 68 | 68 | 67 | 67 | 66 | 66 | 66 | 68 | 68 | 68 | 68 | 68 | 69 | 69 | 68 | 69 | 68 |
| | | | 2012 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 53 | 53 | 53 | 53 | 53 | 53 | 53 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 |
| | | | 2013 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 97 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| | | | 2014 | 81 | 81 | 81 | 81 | 80 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 |
| | | | 2015 | 91 | 92 | 92 | 92 | 92 | 91 | 91 | 92 | 92 | 91 | 90 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 |
| Site 10 | Central (Bangkok) | Roadside | 2011 | 78 | 79 | 79 | 78 | 79 | 78 | 77 | 78 | 77 | 77 | 77 | 78 | 78 | 78 | 79 | 79 | 79 | 80 | 80 | 79 | 79 | 78 | 77 | 78 | 78 |
| | | | 2012 | 67 | 68 | 67 | 67 | 67 | 67 | 68 | 68 | 67 | 67 | 65 | 64 | 64 | 66 | 67 | 66 | 66 | 66 | 65 | 65 | 66 | 68 | 67 | 67 | 67 |
| | | | 2013 | 61 | 59 | 59 | 59 | 61 | 61 | 61 | 61 | 61 | 61 | 59 | 59 | 61 | 62 | 62 | 63 | 63 | 64 | 64 | 62 | 61 | 62 | 61 | 61 | 58 |
| | | | 2014 | 85 | 85 | 85 | 85 | 84 | 84 | 85 | 85 | 85 | 85 | 85 | 85 | 84 | 84 | 85 | 84 | 85 | 85 | 85 | 85 | 86 | 85 | 85 | 85 | 85 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2015 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 18 | 18 | 18 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 |
| Site 11 | Central (Bangkok) | Roadside Site | 2011 | 70 | 70 | 70 | 70 | 70 | 70 | 69 | 67 | 66 | 68 | 70 | 69 | 70 | 70 | 71 | 71 | 71 | 71 | 71 | 71 | 71 | 70 | 70 | 71 | 70 | 70 |
| | | | 2012 | 50 | 51 | 51 | 51 | 50 | 50 | 50 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 50 | 50 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 |
| | | | 2013 | 71 | 73 | 72 | 71 | 72 | 72 | 72 | 71 | 72 | 72 | 71 | 71 | 70 | 71 | 71 | 70 | 70 | 71 | 72 | 72 | 73 | 72 | 72 | 71 | 71 | 71 |
| | | | 2014 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 73 | 73 | 73 | 72 | 72 | 71 | 72 | 72 | 71 | 70 | 70 | 71 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| | | | 2015 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 68 | 68 | 69 | 68 | 69 | 68 | 68 | 68 | 68 | 68 | 69 | 68 | 70 | 70 |
| Site 12 | Central (Bangkok) | Roadside Site | 2011 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 97 | 97 | 96 | 97 | 97 | 98 | 97 | 98 | 97 | 98 | 98 | 98 | 98 | 98 | 97 | 98 | 97 |
| | | | 2012 | 88 | 89 | 89 | 88 | 88 | 88 | 88 | 89 | 89 | 89 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 89 | 89 | 89 | 89 | 88 | 89 | 89 | 88 |
| | | | 2013 | 93 | 94 | 94 | 94 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 94 | 93 | 93 | 93 | 94 | 94 | 95 | 94 | 93 | 94 | 94 |
| | | | 2014 | 87 | 87 | 87 | 87 | 87 | 87 | 88 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 88 | 88 | 88 | 87 | 87 | 88 | 88 | 88 | 88 | 88 | 87 |
| | | | 2015 | 41 | 41 | 41 | 41 | 41 | 40 | 41 | 41 | 40 | 41 | 40 | 40 | 40 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 |
| Site 13 | Central (Bangkok) | Roadside Site | 2012 | 67 | 72 | 72 | 72 | 72 | 72 | 72 | 71 | 53 | 41 | 45 | 59 | 66 | 70 | 71 | 71 | 71 | 71 | 68 | 68 | 70 | 72 | 72 | 72 | 72 |
| Site 14 | Central (Bangkok) | Roadside Site | 2011 | 77 | 77 | 77 | 77 | 77 | 77 | 77 | 77 | 76 | 77 | 76 | 76 | 76 | 77 | 76 | 76 | 77 | 77 | 77 | 77 | 77 | 77 | 77 | 77 | 77 |
| | | | 2012 | 75 | 75 | 75 | 75 | 75 | 74 | 75 | 74 | 75 | 75 | 74 | 74 | 73 | 73 | 73 | 73 | 74 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| | | | 2013 | 70 | 72 | 72 | 71 | 72 | 72 | 71 | 71 | 71 | 71 | 70 | 68 | 66 | 67 | 67 | 69 | 69 | 69 | 72 | 72 | 72 | 73 | 73 | 72 | 72 |
| | | | 2014 | 74 | 75 | 75 | 75 | 75 | 75 | 75 | 74 | 74 | 74 | 74 | 74 | 73 | 73 | 74 | 74 | 75 | 75 | 75 | 74 | 75 | 75 | 75 | 75 | 75 |
| | | | 2015 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 99 | 99 |
| Site 15 | Central (Bangkok) | Roadside Site | 2011 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| | | | 2012 | 71 | 71 | 71 | 71 | 71 | 71 | 71 | 71 | 71 | 71 | 70 | 70 | 71 | 70 | 70 | 70 | 68 | 67 | 70 | 71 | 71 | 71 | 70 | 71 | 71 |
| | | | 2013 | 95 | 96 | 96 | 95 | 95 | 95 | 95 | 96 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 |
| | | | 2014 | 94 | 94 | 94 | 95 | 95 | 95 | 93 | 93 | 94 | 93 | 94 | 93 | 94 | 95 | 96 | 96 | 95 | 95 | 95 | 95 | 96 | 95 | 94 | 95 | 94 |
| | | | 2015 | 58 | 58 | 58 | 58 | 58 | 58 | 58 | 59 | 59 | 58 | 58 | 57 | 57 | 58 | 58 | 58 | 58 | 58 | 58 | 58 | 58 | 58 | 58 | 58 | 58 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 16 | Central (Bangkok) | Roadside | 2011 | 83 | 82 | 82 | 83 | 83 | 83 | 81 | 83 | 83 | 83 | 82 | 84 | 84 | 83 | 84 | 84 | 85 | 85 | 84 | 83 | 85 | 83 | 82 | 83 | 82 |
| | | | 2012 | 94 | 91 | 93 | 92 | 92 | 93 | 93 | 94 | 94 | 93 | 93 | 93 | 94 | 93 | 94 | 94 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 94 | 93 |
| | | | 2013 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 98 | 99 | 99 | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 98 | 99 |
| | | | 2014 | 93 | 90 | 93 | 92 | 92 | 93 | 93 | 93 | 93 | 94 | 94 | 93 | 94 | 93 | 94 | 93 | 94 | 95 | 94 | 94 | 94 | 94 | 94 | 93 | 92 |
| | | | 2015 | 99 | 98 | 98 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 99 | 98 | 98 | 98 | 99 | 98 | 99 | 99 | 99 | 98 | 98 | 99 | 99 | 99 | 98 |
| Site 17 | Central (Bangkok) | General Site | 2011 | 25 | 25 | 25 | 26 | 26 | 26 | 25 | 25 | 25 | 25 | 25 | 24 | 24 | 24 | 25 | 25 | 25 | 25 | 26 | 26 | 26 | 26 | 26 | 26 | 25 |
| | | | 2012 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 |
| | | | 2013 | 87 | 80 | 86 | 86 | 87 | 87 | 87 | 88 | 88 | 86 | 85 | 84 | 87 | 88 | 87 | 88 | 89 | 89 | 89 | 90 | 89 | 89 | 87 | 88 | 88 |
| | | | 2014 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 51 | 52 | 51 | 52 | 51 | 51 | 51 | 51 | 51 | 51 | 51 |
| | | | 2015 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 100 | 100 | 100 | 100 | 99 | 99 | 99 | 100 | 99 |
| Site 18 | Central (Bangkok) | General Site | 2011 | 48 | 48 | 48 | 48 | 49 | 48 | 48 | 48 | 48 | 49 | 48 | 48 | 48 | 48 | 49 | 48 | 48 | 48 | 48 | 48 | 49 | 48 | 48 | 48 | 47 |
| | | | 2012 | 47 | 46 | 48 | 48 | 47 | 48 | 48 | 48 | 48 | 47 | 47 | 48 | 48 | 48 | 47 | 47 | 47 | 47 | 47 | 48 | 48 | 48 | 48 | 47 | 47 |
| | | | 2013 | 95 | 93 | 96 | 97 | 96 | 97 | 97 | 97 | 95 | 96 | 96 | 92 | 96 | 97 | 96 | 93 | 93 | 93 | 95 | 95 | 97 | 96 | 96 | 95 | 93 |
| | | | 2014 | 97 | 98 | 97 | 97 | 98 | 98 | 98 | 98 | 97 | 97 | 95 | 92 | 97 | 96 | 96 | 95 | 95 | 96 | 96 | 97 | 97 | 98 | 97 | 96 | 97 |
| | | | 2015 | 89 | 88 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 88 | 88 | 88 | 87 | 88 | 88 | 88 | 89 | 89 | 89 | 89 | 89 | 89 | 89 |
| Site 19 | Central | General Site | 2011 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 85 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 |
| | | | 2012 | 96 | 98 | 98 | 97 | 97 | 97 | 98 | 98 | 97 | 96 | 96 | 94 | 94 | 94 | 94 | 95 | 94 | 94 | 95 | 95 | 95 | 95 | 96 | 97 | 96 |
| | | | 2013 | 91 | 92 | 91 | 90 | 92 | 92 | 92 | 92 | 92 | 86 | 87 | 90 | 91 | 92 | 92 | 92 | 93 | 92 | 93 | 93 | 92 | 92 | 92 | 92 | 92 |
| | | | 2014 | 91 | 90 | 93 | 92 | 93 | 93 | 94 | 94 | 89 | 70 | 83 | 92 | 91 | 93 | 93 | 93 | 91 | 92 | 91 | 95 | 94 | 93 | 91 | 92 | 89 |
| | | | 2015 | 86 | 87 | 87 | 88 | 86 | 88 | 88 | 88 | 88 | 71 | 78 | 84 | 86 | 88 | 87 | 87 | 87 | 86 | 87 | 86 | 86 | 86 | 87 | 89 | 87 |
| Site 20 | Central | General Site | 2011 | 99 | 100 | 100 | 100 | 100 | 99 | 100 | 100 | 99 | 92 | 95 | 98 | 96 | 99 | 99 | 99 | 100 | 99 | 100 | 99 | 99 | 100 | 100 | 100 | 100 |
| | | | 2012 | 85 | 87 | 86 | 88 | 88 | 88 | 87 | 87 | 82 | 69 | 70 | 81 | 84 | 85 | 87 | 85 | 86 | 86 | 86 | 87 | 87 | 87 | 87 | 87 | 87 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2013 | 91 | 89 | 88 | 89 | 89 | 88 | 89 | 91 | 91 | 92 | 92 | 91 | 91 | 90 | 90 | 89 | 90 | 92 | 92 | 92 | 93 | 93 | 92 | 91 | 90 |
| | | | 2014 | 87 | 85 | 86 | 87 | 85 | 85 | 85 | 87 | 88 | 88 | 87 | 87 | 87 | 87 | 86 | 84 | 86 | 87 | 88 | 88 | 87 | 86 | 88 | 87 | 87 |
| | | | 2015 | 45 | 43 | 45 | 42 | 41 | 43 | 42 | 44 | 45 | 45 | 44 | 44 | 45 | 45 | 46 | 46 | 46 | 46 | 46 | 47 | 46 | 45 | 45 | 45 | 44 |
| Site 21 | Central | General Site | 2011 | 75 | 75 | 75 | 75 | 75 | 76 | 76 | 76 | 76 | 75 | 75 | 74 | 75 | 75 | 74 | 74 | 74 | 74 | 73 | 74 | 74 | 74 | 74 | 74 | 75 |
| | | | 2012 | 41 | 42 | 42 | 42 | 42 | 42 | 42 | 42 | 41 | 41 | 41 | 41 | 41 | 41 | 40 | 40 | 39 | 40 | 41 | 40 | 40 | 41 | 41 | 41 | 41 |
| | | | 2013 | 94 | 95 | 96 | 95 | 95 | 95 | 94 | 95 | 96 | 96 | 95 | 95 | 93 | 93 | 89 | 95 | 94 | 94 | 95 | 93 | 95 | 95 | 95 | 95 | 96 |
| | | | 2014 | 94 | 95 | 93 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 94 | 93 | 90 | 92 | 88 | 89 | 89 | 94 | 93 | 94 | 93 | 96 | 96 | 96 | 95 |
| | | | 2015 | 73 | 74 | 74 | 75 | 73 | 74 | 74 | 75 | 74 | 75 | 75 | 74 | 73 | 75 | 69 | 68 | 71 | 74 | 72 | 72 | 72 | 73 | 74 | 74 | 74 |
| Site 22 | Central | General Site | 2011 | 86 | 86 | 86 | 87 | 87 | 86 | 86 | 86 | 84 | 85 | 86 | 84 | 84 | 84 | 83 | 84 | 86 | 86 | 87 | 87 | 87 | 87 | 87 | 87 | 87 |
| | | | 2012 | 91 | 92 | 90 | 92 | 92 | 92 | 92 | 92 | 88 | 90 | 90 | 89 | 88 | 90 | 91 | 90 | 92 | 93 | 93 | 93 | 92 | 92 | 92 | 92 | 92 |
| | | | 2013 | 79 | 78 | 80 | 81 | 80 | 77 | 80 | 80 | 75 | 77 | 76 | 74 | 75 | 77 | 77 | 79 | 79 | 80 | 81 | 81 | 81 | 81 | 80 | 81 | 81 |
| | | | 2014 | 72 | 72 | 73 | 69 | 72 | 70 | 73 | 73 | 73 | 73 | 73 | 72 | 72 | 70 | 70 | 64 | 71 | 72 | 73 | 74 | 75 | 74 | 74 | 74 | 74 |
| Site 23 | Central | General Site | 2011 | 75 | 76 | 75 | 75 | 75 | 75 | 75 | 75 | 74 | 75 | 74 | 74 | 73 | 73 | 73 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| | | | 2012 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 90 | 90 | 90 | 90 | 90 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 |
| | | | 2013 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 92 |
| | | | 2014 | 97 | 97 | 97 | 97 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 98 | 98 | 98 | 98 | 98 | 97 | 97 |
| | | | 2015 | 84 | 84 | 84 | 83 | 84 | 84 | 85 | 85 | 85 | 85 | 85 | 84 | 83 | 84 | 85 | 84 | 84 | 84 | 82 | 84 | 83 | 84 | 83 | 82 | 82 |
| Site 24 | Central | General Site | 2011 | 86 | 87 | 88 | 88 | 88 | 88 | 88 | 88 | 87 | 82 | 81 | 85 | 83 | 84 | 85 | 87 | 88 | 88 | 87 | 87 | 87 | 87 | 87 | 87 | 87 |
| | | | 2012 | 98 | 100 | 100 | 98 | 99 | 99 | 100 | 100 | 98 | 90 | 93 | 96 | 98 | 97 | 97 | 97 | 98 | 100 | 99 | 99 | 99 | 98 | 99 | 99 | 98 |
| | | | 2013 | 98 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 99 | 99 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 98 | 97 | 97 | 97 | 98 | 99 | 99 | 99 |
| | | | 2014 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 100 | 100 | 100 |
| | | | 2015 | 100 | 99 | 99 | 100 | 100 | 100 | 100 | 99 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 25 | Central | General Site | 2011 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 84 | 84 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| | | | 2012 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 95 | 95 | 95 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 |
| | | | 2013 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 94 | 94 | 93 | 94 | 94 | 94 | 94 | 95 | 96 | 96 | 96 | 95 | 95 | 95 |
| | | | 2014 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 92 | 92 | 93 | 93 | 94 | 94 | 94 | 94 | 93 | 91 | 92 | 94 | 93 | 93 |
| | | | 2015 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 96 | 95 | 96 | 95 | 95 | 95 | 95 | 95 | 95 | 95 |
| Site 26 | Central | General Site | 2011 | 87 | 86 | 87 | 86 | 85 | 88 | 88 | 88 | 87 | 88 | 87 | 87 | 86 | 85 | 86 | 85 | 86 | 87 | 88 | 88 | 88 | 87 | 87 | 88 | 88 |
| | | | 2012 | 96 | 96 | 93 | 95 | 95 | 96 | 95 | 96 | 98 | 98 | 96 | 96 | 96 | 98 | 96 | 97 | 97 | 96 | 97 | 96 | 97 | 97 | 97 | 95 | 96 |
| | | | 2013 | 96 | 97 | 95 | 96 | 97 | 96 | 96 | 96 | 97 | 97 | 97 | 96 | 96 | 96 | 96 | 96 | 97 | 96 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |
| | | | 2014 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 99 | 98 | 99 | 98 | 98 | 98 | 99 | 100 | 100 | 99 | 100 | 100 | 99 | 99 | 100 | 100 | 99 | 99 |
| | | | 2015 | 78 | 78 | 77 | 77 | 79 | 79 | 78 | 79 | 78 | 78 | 77 | 77 | 76 | 77 | 77 | 78 | 79 | 79 | 80 | 80 | 80 | 80 | 79 | 79 | 79 |
| Site 27 | Central | General Site | 2011 | 84 | 84 | 85 | 84 | 84 | 84 | 84 | 85 | 85 | 83 | 82 | 83 | 83 | 84 | 83 | 84 | 84 | 85 | 85 | 85 | 85 | 85 | 85 | 84 | 83 |
| | | | 2012 | 51 | 51 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 49 | 47 | 49 | 51 | 52 | 52 | 52 | 51 | 51 | 51 | 52 | 52 | 51 | 52 | 52 | 52 |
| | | | 2013 | 89 | 89 | 87 | 88 | 87 | 88 | 89 | 89 | 89 | 90 | 90 | 89 | 89 | 88 | 88 | 89 | 89 | 90 | 90 | 90 | 91 | 90 | 90 | 89 | 89 |
| | | | 2014 | 93 | 94 | 92 | 93 | 92 | 92 | 94 | 94 | 94 | 94 | 94 | 92 | 92 | 90 | 90 | 93 | 92 | 93 | 94 | 94 | 94 | 94 | 94 | 94 | 93 |
| | | | 2015 | 82 | 82 | 80 | 81 | 81 | 81 | 82 | 83 | 82 | 82 | 82 | 82 | 81 | 78 | 78 | 78 | 80 | 82 | 85 | 85 | 85 | 85 | 84 | 83 | 83 |
| Site 28 | Central | General Site | 2013 | 99 | 100 | 99 | 100 | 100 | 100 | 100 | 100 | 99 | 100 | 98 | 99 | 98 | 97 | 97 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 100 |
| | | | 2014 | 97 | 98 | 98 | 98 | 98 | 97 | 97 | 97 | 97 | 96 | 97 | 97 | 96 | 96 | 97 | 96 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 |
| | | | 2015 | 91 | 92 | 91 | 92 | 91 | 91 | 91 | 91 | 91 | 90 | 91 | 90 | 90 | 90 | 92 | 91 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 |
| Site 29 | Central | General Site | 2011 | 90 | 88 | 91 | 91 | 90 | 91 | 91 | 90 | 92 | 91 | 88 | 86 | 88 | 86 | 89 | 90 | 91 | 91 | 90 | 91 | 92 | 91 | 90 | 89 | 89 |
| | | | 2012 | 85 | 85 | 85 | 85 | 86 | 85 | 85 | 85 | 85 | 85 | 84 | 85 | 85 | 86 | 85 | 84 | 86 | 86 | 84 | 85 | 86 | 85 | 86 | 85 | 84 |
| | | | 2013 | 61 | 60 | 60 | 62 | 62 | 62 | 61 | 61 | 62 | 62 | 60 | 61 | 61 | 62 | 61 | 62 | 62 | 62 | 62 | 61 | 61 | 61 | 61 | 60 | 61 |
| Site 30 | North | | 2011 | 99 | 99 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | General Site | 2012 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 97 | 96 | 97 | 97 | 97 | 96 | 97 | 96 | 98 | 97 | 98 | 98 | 98 | 98 | 98 |
| | | | 2013 | 94 | 95 | 94 | 94 | 94 | 94 | 94 | 94 | 94 | 93 | 90 | 92 | 94 | 93 | 93 | 93 | 93 | 94 | 94 | 95 | 95 | 95 | 95 | 95 | 95 |
| | | | 2014 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 92 | 95 | 96 | 95 | 95 | 96 | 96 | 95 | 97 | 96 | 96 | 97 | 96 | 95 | 96 | 95 |
| | | | 2015 | 91 | 92 | 92 | 91 | 92 | 92 | 92 | 92 | 92 | 90 | 90 | 91 | 90 | 91 | 90 | 90 | 90 | 90 | 91 | 91 | 92 | 91 | 92 | 92 | 92 |
| Site 31 | North | General Site | 2011 | 43 | 42 | 44 | 43 | 42 | 41 | 41 | 42 | 44 | 45 | 44 | 44 | 44 | 45 | 44 | 43 | 45 | 45 | 44 | 44 | 43 | 44 | 43 | 43 | 44 |
| | | | 2012 | 81 | 82 | 82 | 83 | 77 | 75 | 72 | 81 | 82 | 84 | 83 | 84 | 84 | 84 | 82 | 81 | 81 | 81 | 84 | 84 | 84 | 84 | 81 | 80 | 81 |
| | | | 2013 | 85 | 84 | 85 | 85 | 83 | 82 | 82 | 86 | 86 | 86 | 87 | 85 | 85 | 85 | 86 | 87 | 84 | 83 | 84 | 87 | 86 | 88 | 86 | 84 | 83 |
| | | | 2014 | 92 | 88 | 87 | 92 | 93 | 92 | 86 | 85 | 85 | 94 | 96 | 97 | 95 | 95 | 93 | 95 | 96 | 95 | 92 | 90 | 93 | 95 | 95 | 95 | 90 |
| | | | 2015 | 68 | 68 | 68 | 66 | 66 | 64 | 65 | 67 | 67 | 68 | 68 | 68 | 69 | 69 | 69 | 69 | 67 | 67 | 68 | 68 | 68 | 69 | 68 | 69 | 69 |
| Site 32 | North | General Site | 2011 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 94 | 95 | 95 | 96 | 95 | 96 | 95 | 95 | 95 | 95 | 95 | 95 | 96 | 95 | 95 |
| | | | 2012 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 96 | 96 | 95 | 93 | 93 | 93 | 94 | 96 | 96 | 96 | 96 | 96 | 96 |
| | | | 2013 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| | | | 2014 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 |
| | | | 2015 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| Site 33 | North | General Site | 2011 | 97 | 96 | 97 | 97 | 96 | 96 | 97 | 97 | 98 | 97 | 96 | 96 | 96 | 97 | 98 | 98 | 97 | 97 | 97 | 97 | 98 | 98 | 98 | 98 | 96 |
| | | | 2012 | 95 | 95 | 96 | 96 | 95 | 96 | 96 | 96 | 96 | 96 | 94 | 94 | 95 | 95 | 96 | 95 | 95 | 96 | 95 | 95 | 96 | 96 | 96 | 96 | 96 |
| | | | 2013 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 96 | 96 | 96 | 97 | 97 | 97 | 97 | 98 | 98 | 98 | 98 | 98 | 98 |
| | | | 2014 | 92 | 93 | 93 | 93 | 93 | 93 | 92 | 92 | 92 | 89 | 90 | 91 | 90 | 92 | 92 | 92 | 93 | 92 | 93 | 93 | 93 | 93 | 93 | 93 | 93 |
| | | | 2015 | 98 | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| Site 34 | North | General Site | 2013 | 91 | 91 | 91 | 90 | 90 | 89 | 90 | 90 | 90 | 90 | 90 | 90 | 91 | 90 | 90 | 90 | 90 | 91 | 92 | 92 | 92 | 92 | 92 | 92 | 92 |
| | | | 2014 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 96 | 96 | 96 | 96 | 96 | 97 | 96 | 97 | 96 | 97 | 97 | 96 | 96 | 96 | 95 | 96 | 96 |
| | | | 2015 | 91 | 90 | 90 | 92 | 92 | 91 | 91 | 91 | 91 | 90 | 91 | 90 | 91 | 90 | 90 | 90 | 89 | 90 | 92 | 92 | 92 | 92 | 92 | 91 | 91 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 35 | North | General Site | 2011 | 79 | 79 | 79 | 80 | 80 | 80 | 80 | 80 | 79 | 79 | 79 | 79 | 79 | 78 | 79 | 78 | 78 | 78 | 78 | 79 | 79 | 80 | 80 | 80 | 80 |
| | | | 2012 | 85 | 89 | 89 | 89 | 89 | 90 | 90 | 90 | 88 | 79 | 69 | 71 | 79 | 84 | 86 | 83 | 83 | 84 | 86 | 88 | 87 | 88 | 89 | 89 | 88 |
| Site 36 | North | General Site | 2011 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 96 | 96 | 96 | 95 | 96 | 96 | 96 | 96 |
| | | | 2012 | 99 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 98 | 99 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 100 | 99 | 99 | 99 | 99 | 99 | 99 |
| | | | 2013 | 90 | 91 | 91 | 91 | 91 | 92 | 91 | 91 | 90 | 89 | 88 | 88 | 88 | 88 | 88 | 89 | 89 | 90 | 89 | 90 | 91 | 91 | 91 | 91 | 90 |
| | | | 2014 | 95 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 94 | 95 | 94 | 94 | 95 | 95 | 94 | 96 | 96 | 95 | 95 | 96 | 95 | 96 | 96 | 96 |
| | | | 2015 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 97 | 97 | 98 | 97 | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 99 |
| Site 37 | North | General Site | 2015 | 98 | 100 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 98 | 98 | 96 | 95 | 97 | 97 | 98 | 97 | 97 | 97 | 99 | 98 | 98 | 99 | 99 | 100 |
| Site 38 | North | General Site | 2011 | 92 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 92 | 90 | 91 | 91 | 91 | 91 | 90 | 90 | 91 | 91 | 92 | 93 | 91 | 92 | 93 | 93 |
| | | | 2012 | 78 | 78 | 79 | 79 | 79 | 79 | 80 | 80 | 81 | 80 | 78 | 77 | 76 | 77 | 77 | 77 | 77 | 78 | 78 | 77 | 78 | 77 | 77 | 77 | 78 |
| | | | 2013 | 91 | 91 | 91 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 91 | 91 | 91 | 90 | 91 | 91 | 92 | 92 | 91 | 90 | 90 | 90 |
| | | | 2014 | 96 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 96 | 96 | 96 | 96 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 96 | 96 | 96 | 96 | 95 |
| | | | 2015 | 98 | 98 | 98 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 |
| Site 39 | North | General Site | 2011 | 95 | 96 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 95 | 94 | 93 | 94 | 93 | 92 | 92 | 93 | 93 | 94 | 94 | 95 | 96 | 97 | 97 |
| | | | 2012 | 77 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 79 | 78 | 75 | 75 | 73 | 75 | 76 | 77 | 77 | 78 | 78 | 76 | 76 | 77 | 77 | 77 | 78 |
| | | | 2013 | 99 | 99 | 99 | 98 | 99 | 98 | 99 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 98 | 98 | 98 | 99 | 99 | 98 | 99 | 98 | 98 | 99 | 98 |
| | | | 2014 | 91 | 92 | 92 | 92 | 92 | 93 | 93 | 93 | 93 | 92 | 90 | 91 | 90 | 91 | 91 | 90 | 89 | 88 | 88 | 89 | 89 | 90 | 91 | 92 | 92 |
| | | | 2015 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 87 | 87 | 88 | 88 | 87 | 88 | 87 | 88 | 87 | 88 | 88 | 88 | 89 | 89 | 89 |
| Site 40 | North | General Site | 2011 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 98 | 95 | 98 | 99 | 99 | 98 | 97 | 98 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| | | | 2012 | 94 | 94 | 94 | 94 | 95 | 95 | 95 | 96 | 95 | 92 | 90 | 92 | 92 | 94 | 94 | 91 | 93 | 93 | 94 | 95 | 94 | 93 | 93 | 95 | 94 |
| | | | 2013 | 89 | 91 | 91 | 91 | 91 | 92 | 92 | 90 | 88 | 88 | 87 | 88 | 90 | 90 | 88 | 87 | 88 | 88 | 90 | 90 | 88 | 89 | 89 | 90 | 90 |
| | | | 2014 | 98 | 99 | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 96 | 96 | 96 | 97 | 97 | 97 | 97 | 98 | 95 | 96 | 97 | 98 | 98 | 99 | 99 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2015 | 72 | 71 | 73 | 74 | 74 | 73 | 74 | 75 | 75 | 73 | 73 | 73 | 73 | 73 | 72 | 73 | 72 | 70 | 71 | 70 | 70 | 67 | 68 | 68 | 71 |
| Site 41 | North | General Site | 2013 | 91 | 92 | 92 | 91 | 92 | 92 | 92 | 92 | 92 | 92 | 91 | 91 | 92 | 92 | 91 | 92 | 91 | 91 | 90 | 90 | 91 | 92 | 92 | 92 | 92 |
| | | | 2014 | 93 | 94 | 93 | 95 | 94 | 94 | 94 | 94 | 95 | 95 | 95 | 94 | 93 | 93 | 93 | 92 | 92 | 92 | 92 | 92 | 92 | 93 | 93 | 95 | 94 |
| | | | 2015 | 96 | 97 | 95 | 95 | 97 | 96 | 97 | 98 | 98 | 98 | 96 | 95 | 96 | 96 | 97 | 96 | 97 | 96 | 97 | 96 | 97 | 97 | 97 | 96 | 96 |
| Site 43 | North | General Site | 2011 | 85 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 84 | 84 | 86 | 86 | 85 | 86 | 86 | 85 | 84 | 83 | 84 | 86 | 86 | 85 | 86 | 85 |
| | | | 2012 | 91 | 92 | 92 | 92 | 89 | 91 | 91 | 91 | 91 | 92 | 93 | 89 | 89 | 85 | 87 | 89 | 91 | 89 | 91 | 92 | 94 | 95 | 94 | 92 | 92 |
| | | | 2013 | 80 | 84 | 82 | 81 | 78 | 81 | 83 | 81 | 84 | 82 | 75 | 68 | 70 | 72 | 74 | 76 | 78 | 80 | 82 | 85 | 86 | 85 | 85 | 86 | 85 |
| | | | 2014 | 93 | 95 | 94 | 95 | 94 | 95 | 96 | 96 | 95 | 93 | 92 | 89 | 90 | 90 | 90 | 92 | 90 | 91 | 90 | 92 | 95 | 96 | 96 | 95 | 95 |
| | | | 2015 | 90 | 90 | 89 | 91 | 92 | 92 | 92 | 92 | 91 | 93 | 90 | 88 | 90 | 89 | 89 | 90 | 88 | 89 | 89 | 91 | 90 | 90 | 91 | 91 | 91 |
| Site 44 | North | General Site | 2011 | 87 | 91 | 90 | 90 | 90 | 90 | 89 | 90 | 90 | 90 | 89 | 84 | 84 | 84 | 80 | 81 | 81 | 84 | 85 | 88 | 89 | 90 | 90 | 90 | 90 |
| | | | 2012 | 83 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 83 | 84 | 82 | 81 | 80 | 81 | 81 | 81 | 82 | 82 | 83 | 84 | 85 | 85 | 84 |
| | | | 2013 | 86 | 89 | 90 | 90 | 90 | 90 | 89 | 90 | 89 | 90 | 88 | 85 | 81 | 79 | 79 | 78 | 79 | 80 | 81 | 84 | 88 | 89 | 90 | 89 | 90 |
| | | | 2014 | 49 | 50 | 49 | 49 | 49 | 49 | 50 | 50 | 50 | 48 | 48 | 48 | 48 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | | | 2015 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 98 | 98 | 99 | 98 | 98 | 98 | 97 | 97 | 97 | 97 | 98 | 98 | 98 | 97 | 96 | 98 | 98 | 96 |
| Site 45 | North | General Site | 2011 | 89 | 89 | 92 | 93 | 92 | 93 | 93 | 92 | 90 | 86 | 86 | 85 | 84 | 83 | 84 | 84 | 83 | 85 | 88 | 91 | 93 | 93 | 92 | 90 | 88 |
| | | | 2012 | 94 | 96 | 96 | 96 | 94 | 94 | 95 | 95 | 95 | 95 | 91 | 92 | 90 | 90 | 90 | 90 | 92 | 92 | 94 | 95 | 94 | 96 | 96 | 96 | 96 |
| | | | 2013 | 54 | 55 | 56 | 56 | 55 | 55 | 55 | 55 | 55 | 53 | 51 | 52 | 53 | 53 | 54 | 54 | 54 | 54 | 54 | 55 | 55 | 55 | 55 | 56 | 56 |
| | | | 2014 | 94 | 95 | 95 | 95 | 96 | 96 | 96 | 94 | 95 | 96 | 96 | 95 | 95 | 94 | 93 | 92 | 93 | 93 | 92 | 93 | 92 | 94 | 94 | 94 | 95 |
| | | | 2015 | 93 | 94 | 94 | 94 | 94 | 93 | 93 | 94 | 92 | 93 | 92 | 92 | 91 | 92 | 93 | 93 | 93 | 93 | 92 | 92 | 93 | 93 | 93 | 93 | 94 |
| Site 46 | North | General Site | 2011 | 99 | 99 | 100 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 99 | 99 | 100 | 99 |
| | | | 2012 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 97 | 97 | 97 | 98 | 98 | 98 | 98 |
| | | | 2013 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 98 | 99 | 97 | 99 | 99 | 98 | 98 | 96 | 98 | 98 | 99 | 99 | 98 | 98 | 98 | 99 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2014 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 97 | 98 | 98 | 99 | 99 | 98 | 98 | 98 | 97 | 98 | 98 | 99 | 99 | 98 | 99 | 99 |
| | | | 2015 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 86 | 86 | 86 | 87 | 87 | 87 | 87 | 87 | 87 | 86 | 87 | 86 | 85 | 85 | 86 | 87 |
| Site 47 | Central | General Site | 2014 | 99 | 98 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 100 | 99 | 99 | 98 | 100 | 100 | 98 | 99 | 99 | 98 | 98 | 98 | 98 | 98 | 98 |
| | | | 2015 | 96 | 97 | 97 | 96 | 97 | 97 | 96 | 96 | 96 | 97 | 97 | 96 | 95 | 96 | 95 | 95 | 96 | 96 | 97 | 97 | 97 | 96 | 97 | 98 | 98 |
| Site 48 | Central | General Site | 2011 | 95 | 94 | 96 | 96 | 95 | 94 | 96 | 96 | 95 | 93 | 94 | 91 | 91 | 95 | 95 | 95 | 94 | 93 | 95 | 96 | 95 | 96 | 96 | 94 | 94 |
| | | | 2012 | 90 | 92 | 92 | 92 | 92 | 92 | 93 | 93 | 91 | 86 | 79 | 89 | 88 | 90 | 91 | 90 | 90 | 90 | 91 | 93 | 93 | 93 | 90 | 90 | 92 |
| | | | 2013 | 79 | 76 | 80 | 79 | 80 | 80 | 80 | 82 | 80 | 79 | 77 | 77 | 79 | 78 | 78 | 78 | 78 | 78 | 81 | 81 | 80 | 81 | 82 | 81 | 81 |
| | | | 2014 | 63 | 64 | 63 | 64 | 64 | 64 | 62 | 63 | 63 | 63 | 63 | 62 | 63 | 63 | 63 | 64 | 64 | 63 | 64 | 64 | 64 | 64 | 64 | 64 | 63 |
| Site 49 | Central | General Site | 2011 | 95 | 96 | 95 | 95 | 96 | 95 | 95 | 96 | 96 | 95 | 95 | 95 | 95 | 94 | 95 | 95 | 95 | 96 | 96 | 95 | 95 | 95 | 96 | 95 | 96 |
| | | | 2012 | 98 | 99 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 98 | 98 | 98 | 97 | 98 | 98 | 98 | 99 | 98 | 98 | 98 | 99 | 99 | 99 |
| | | | 2013 | 94 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 94 | 94 | 93 | 94 | 94 | 94 | 95 | 95 | 94 | 94 | 95 | 95 | 95 | 95 |
| | | | 2014 | 98 | 98 | 98 | 98 | 97 | 98 | 99 | 98 | 97 | 98 | 98 | 97 | 97 | 97 | 96 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 |
| | | | 2015 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 96 | 96 | 96 | 97 | 97 | 96 | 96 | 96 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |
| Site 50 | Central | General Site | 2011 | 85 | 86 | 85 | 86 | 86 | 87 | 87 | 83 | 82 | 81 | 83 | 84 | 84 | 85 | 86 | 87 | 86 | 86 | 85 | 84 | 84 | 86 | 85 | 87 | 86 |
| | | | 2012 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 88 | 88 | 88 | 88 | 88 | 88 | 89 | 89 | 89 | 88 | 89 | 89 | 89 | 89 |
| | | | 2013 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 97 | 96 | 96 | 96 |
| | | | 2014 | 93 | 93 | 93 | 93 | 93 | 92 | 93 | 93 | 93 | 92 | 91 | 92 | 92 | 92 | 92 | 92 | 92 | 93 | 93 | 94 | 94 | 94 | 93 | 93 | 93 |
| | | | 2015 | 95 | 95 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 94 | 95 | 95 | 96 | 96 | 96 | 95 |
| Site 51 | Central | General Site | 2011 | 76 | 76 | 76 | 75 | 76 | 76 | 76 | 77 | 76 | 76 | 75 | 76 | 76 | 76 | 75 | 75 | 75 | 76 | 76 | 75 | 75 | 76 | 75 | 75 | 75 |
| | | | 2013 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 92 | 92 | 92 | 92 | 92 | 93 | 92 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 93 |
| | | | 2014 | 98 | 99 | 97 | 98 | 98 | 98 | 98 | 99 | 98 | 99 | 98 | 98 | 98 | 98 | 98 | 96 | 97 | 98 | 98 | 98 | 98 | 99 | 98 | 98 | 98 |
| | | | 2015 | 87 | 87 | 86 | 87 | 86 | 86 | 87 | 87 | 86 | 86 | 86 | 85 | 86 | 85 | 86 | 87 | 87 | 87 | 88 | 88 | 88 | 87 | 87 | 87 | 87 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 52 | East | General Site | 2014 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 99 | 99 | 100 | 99 | 100 | 100 | 100 | 99 | 99 | 98 | 100 | 100 | 100 |
| | | | 2015 | 95 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 93 | 94 | 93 | 93 | 93 | 94 | 95 | 95 | 95 | 96 | 96 | 96 | 96 | 96 |
| Site 53 | East | General Site | 2011 | 93 | 97 | 96 | 96 | 95 | 95 | 94 | 96 | 94 | 83 | 74 | 86 | 88 | 93 | 93 | 92 | 93 | 95 | 95 | 95 | 96 | 94 | 95 | 93 | 90 |
| | | | 2012 | 89 | 92 | 92 | 92 | 91 | 93 | 91 | 90 | 81 | 76 | 73 | 80 | 89 | 90 | 90 | 90 | 91 | 92 | 91 | 92 | 91 | 91 | 91 | 92 | 92 |
| | | | 2013 | 78 | 84 | 84 | 84 | 84 | 83 | 84 | 82 | 74 | 61 | 54 | 58 | 70 | 75 | 74 | 77 | 79 | 82 | 85 | 85 | 84 | 85 | 85 | 84 | 82 |
| | | | 2014 | 89 | 89 | 89 | 89 | 89 | 90 | 90 | 88 | 88 | 89 | 87 | 88 | 87 | 88 | 88 | 88 | 89 | 89 | 89 | 90 | 88 | 89 | 90 | 90 | 90 |
| Site 54 | East | General Site | 2011 | 87 | 87 | 88 | 87 | 87 | 87 | 87 | 87 | 87 | 86 | 85 | 85 | 86 | 86 | 87 | 87 | 88 | 88 | 87 | 87 | 88 | 88 | 88 | 88 | 88 |
| | | | 2012 | 84 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 84 | 84 | 83 | 83 | 83 | 83 | 84 | 83 | 83 | 84 | 84 | 84 | 85 | 85 | 85 | 85 | 85 |
| | | | 2013 | 71 | 72 | 72 | 72 | 71 | 71 | 71 | 71 | 71 | 70 | 69 | 69 | 68 | 69 | 69 | 69 | 70 | 71 | 71 | 71 | 71 | 72 | 72 | 72 | 72 |
| | | | 2014 | 79 | 80 | 80 | 80 | 80 | 79 | 79 | 79 | 79 | 80 | 78 | 78 | 77 | 76 | 75 | 77 | 78 | 79 | 79 | 80 | 80 | 80 | 80 | 80 | 80 |
| | | | 2015 | 70 | 71 | 71 | 71 | 71 | 71 | 71 | 71 | 71 | 71 | 70 | 69 | 69 | 69 | 70 | 68 | 69 | 70 | 70 | 70 | 71 | 71 | 71 | 71 | 71 |
| Site 55 | East | General Site | 2013 | 98 | 100 | 99 | 99 | 98 | 98 | 98 | 99 | 98 | 99 | 97 | 98 | 98 | 98 | 97 | 95 | 97 | 98 | 97 | 98 | 99 | 99 | 99 | 99 | 99 |
| | | | 2014 | 98 | 99 | 99 | 98 | 98 | 98 | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 98 | 98 | 99 | 99 | 99 | 99 | 98 | 98 |
| | | | 2015 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 98 | 97 | 97 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| Site 56 | East | General Site | 2011 | 92 | 93 | 91 | 92 | 92 | 91 | 92 | 92 | 92 | 93 | 89 | 88 | 87 | 89 | 89 | 92 | 92 | 94 | 94 | 95 | 95 | 96 | 95 | 95 | 95 |
| | | | 2012 | 91 | 93 | 92 | 92 | 93 | 93 | 94 | 94 | 93 | 92 | 91 | 84 | 82 | 89 | 92 | 92 | 92 | 92 | 89 | 89 | 88 | 88 | 91 | 93 | 93 |
| | | | 2013 | 82 | 84 | 84 | 85 | 85 | 83 | 83 | 83 | 81 | 81 | 82 | 80 | 80 | 79 | 81 | 82 | 84 | 83 | 81 | 80 | 80 | 81 | 82 | 84 | 82 |
| Site 57 | East | General Site | 2015 | 96 | 97 | 96 | 96 | 96 | 97 | 96 | 97 | 96 | 96 | 95 | 96 | 96 | 95 | 93 | 96 | 95 | 96 | 96 | 97 | 97 | 97 | 97 | 96 | 97 |
| Site 58 | East | General Site | 2011 | 94 | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 94 | 95 | 94 | 94 | 94 | 94 | 94 | 95 | 95 | 95 | 95 | 95 | 94 | 94 | 95 | 94 | 94 |
| | | | 2012 | 93 | 93 | 94 | 93 | 94 | 94 | 94 | 94 | 94 | 94 | 92 | 92 | 91 | 92 | 92 | 92 | 93 | 94 | 94 | 93 | 94 | 94 | 94 | 94 | 93 |
| | | | 2013 | 78 | 79 | 77 | 79 | 78 | 77 | 77 | 78 | 77 | 76 | 77 | 76 | 77 | 78 | 78 | 80 | 80 | 80 | 81 | 81 | 81 | 80 | 80 | 79 | 79 |
| | | | 2014 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 78 | 78 | 76 | 76 | 76 | 76 | 77 | 79 | 81 | 80 | 81 | 81 | 81 | 81 | 81 | 81 | 80 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2015 | 71 | 72 | 71 | 72 | 73 | 73 | 72 | 73 | 73 | 72 | 72 | 69 | 71 | 71 | 71 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 70 | 71 |
| Site 59 | East | General Site | 2014 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 100 | 100 | 100 | 100 | 99 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | | | 2015 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 99 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| Site 60 | East | General Site | 2011 | 94 | 94 | 95 | 94 | 94 | 95 | 93 | 95 | 94 | 94 | 94 | 95 | 93 | 93 | 92 | 93 | 92 | 93 | 94 | 93 | 94 | 94 | 94 | 94 | 95 |
| | | | 2012 | 81 | 81 | 81 | 82 | 82 | 83 | 83 | 83 | 78 | 79 | 79 | 78 | 80 | 81 | 80 | 80 | 80 | 81 | 82 | 83 | 83 | 83 | 82 | 82 | 81 |
| | | | 2013 | 85 | 87 | 87 | 87 | 86 | 87 | 87 | 86 | 85 | 85 | 85 | 84 | 83 | 84 | 84 | 85 | 84 | 85 | 86 | 85 | 86 | 85 | 86 | 86 | 85 |
| | | | 2014 | 72 | 74 | 74 | 74 | 73 | 73 | 70 | 72 | 71 | 72 | 67 | 68 | 70 | 71 | 72 | 73 | 73 | 73 | 73 | 73 | 72 | 72 | 72 | 72 | 73 |
| Site 61 | East | General Site | 2011 | 88 | 87 | 87 | 88 | 86 | 85 | 85 | 87 | 90 | 90 | 90 | 89 | 89 | 88 | 88 | 88 | 88 | 89 | 89 | 90 | 90 | 89 | 89 | 88 | 87 |
| | | | 2012 | 88 | 86 | 87 | 87 | 88 | 88 | 88 | 87 | 89 | 87 | 87 | 86 | 87 | 87 | 87 | 87 | 88 | 87 | 87 | 89 | 88 | 89 | 89 | 89 | 88 |
| | | | 2013 | 74 | 75 | 74 | 74 | 75 | 73 | 74 | 75 | 75 | 74 | 74 | 74 | 74 | 73 | 74 | 73 | 74 | 74 | 74 | 75 | 75 | 76 | 76 | 75 | 75 |
| | | | 2014 | 97 | 97 | 97 | 97 | 97 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 97 | 97 | 96 | 97 | 97 | 97 | 97 | 97 | 97 |
| | | | 2015 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 95 | 96 | 95 | 95 | 95 | 94 | 94 | 95 | 95 | 95 | 96 | 96 | 96 | 96 | 96 | 96 | 96 |
| Site 62 | East | General Site | 2011 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 44 | 44 | 44 | 44 | 44 | 45 | 44 | 44 | 44 | 44 | 44 | 42 | 41 | 42 | 42 | 42 | 42 | 42 |
| | | | 2012 | 97 | 98 | 98 | 98 | 98 | 98 | 97 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 97 | 98 | 98 | 98 | 98 |
| | | | 2013 | 95 | 96 | 95 | 95 | 95 | 96 | 96 | 96 | 96 | 94 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 95 | 96 | 96 | 96 | 95 | 96 |
| | | | 2014 | 90 | 91 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 89 | 89 | 90 | 90 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 | 91 |
| | | | 2015 | 87 | 86 | 85 | 86 | 89 | 85 | 77 | 89 | 84 | 87 | 89 | 90 | 86 | 90 | 88 | 89 | 89 | 89 | 85 | 90 | 85 | 87 | 90 | 87 | 78 |
| Site 64 | East | General Site | 2011 | 75 | 75 | 75 | 75 | 76 | 76 | 75 | 75 | 75 | 73 | 73 | 74 | 75 | 74 | 74 | 76 | 76 | 76 | 76 | 77 | 76 | 74 | 74 | 75 | 75 |
| | | | 2012 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 88 | 89 | 89 | 89 | 88 | 87 | 88 | 89 | 89 | 88 | 90 | 90 | 90 | 89 | 90 | 90 |
| | | | 2013 | 87 | 88 | 88 | 88 | 88 | 88 | 87 | 86 | 86 | 84 | 84 | 84 | 84 | 84 | 85 | 86 | 87 | 88 | 88 | 88 | 88 | 89 | 89 | 88 | 88 |
| | | | 2014 | 88 | 89 | 89 | 89 | 89 | 88 | 89 | 89 | 89 | 89 | 87 | 87 | 87 | 86 | 87 | 87 | 87 | 87 | 88 | 89 | 88 | 89 | 89 | 89 | 89 |
| | | | 2015 | 86 | 87 | 87 | 87 | 87 | 86 | 86 | 87 | 87 | 87 | 84 | 84 | 84 | 82 | 83 | 85 | 84 | 86 | 86 | 87 | 87 | 87 | 87 | 87 | 88 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site 65 | East | General Site | 2011 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 14 | 15 | 15 | 15 | 15 |
| | | | 2012 | 98 | 99 | 99 | 98 | 98 | 98 | 98 | 99 | 99 | 98 | 97 | 96 | 92 | 96 | 99 | 97 | 96 | 96 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| | | | 2013 | 98 | 99 | 97 | 98 | 98 | 98 | 97 | 98 | 99 | 99 | 98 | 98 | 99 | 99 | 98 | 98 | 98 | 98 | 91 | 98 | 99 | 99 | 99 | 99 | 98 |
| | | | 2014 | 94 | 94 | 90 | 92 | 92 | 93 | 95 | 95 | 93 | 96 | 95 | 93 | 95 | 94 | 93 | 95 | 95 | 95 | 95 | 93 | 93 | 94 | 94 | 93 | 94 |
| | | | 2015 | 86 | 81 | 84 | 84 | 86 | 86 | 84 | 85 | 87 | 87 | 87 | 88 | 88 | 87 | 84 | 86 | 87 | 86 | 85 | 87 | 85 | 87 | 87 | 84 | 82 |
| Site 66 | East | General Site | 2011 | 42 | 42 | 43 | 39 | 41 | 38 | 42 | 44 | 43 | 43 | 42 | 44 | 43 | 43 | 44 | 44 | 44 | 43 | 43 | 42 | 42 | 42 | 43 | 41 | 42 |
| | | | 2012 | 80 | 81 | 84 | 85 | 75 | 66 | 66 | 83 | 86 | 86 | 84 | 79 | 80 | 84 | 85 | 86 | 84 | 79 | 81 | 85 | 85 | 84 | 77 | 71 | 69 |
| | | | 2013 | 84 | 84 | 84 | 80 | 82 | 81 | 79 | 86 | 87 | 85 | 81 | 81 | 82 | 85 | 86 | 86 | 85 | 85 | 85 | 86 | 87 | 85 | 86 | 86 | 85 |
| | | | 2014 | 98 | 98 | 98 | 97 | 98 | 98 | 98 | 98 | 99 | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 98 | 98 | 98 | 98 | 98 |
| | | | 2015 | 97 | 96 | 95 | 96 | 95 | 95 | 95 | 96 | 98 | 98 | 98 | 98 | 98 | 98 | 97 | 97 | 98 | 98 | 97 | 97 | 96 | 97 | 97 | 96 | 96 |
| Site 67 | Northeast | General Site | 2013 | 89 | 89 | 92 | 91 | 89 | 87 | 89 | 89 | 88 | 86 | 88 | 88 | 90 | 89 | 92 | 89 | 89 | 89 | 90 | 92 | 89 | 91 | 87 | 87 | 88 |
| | | | 2014 | 93 | 94 | 94 | 94 | 94 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 92 | 92 | 93 | 92 | 93 | 92 | 93 | 93 | 94 | 94 | 94 | 93 | 93 |
| | | | 2015 | 95 | 96 | 96 | 96 | 96 | 96 | 96 | 95 | 96 | 95 | 95 | 95 | 96 | 94 | 93 | 94 | 93 | 93 | 95 | 95 | 95 | 95 | 95 | 95 | 95 |
| Site 68 | Northeast | General Site | 2011 | 86 | 86 | 85 | 86 | 86 | 85 | 86 | 86 | 86 | 85 | 85 | 85 | 86 | 85 | 85 | 86 | 86 | 86 | 87 | 87 | 86 | 86 | 85 | 85 | 86 |
| | | | 2012 | 91 | 92 | 91 | 92 | 92 | 93 | 91 | 91 | 92 | 92 | 89 | 89 | 89 | 88 | 87 | 89 | 90 | 92 | 90 | 90 | 91 | 93 | 92 | 92 | 92 |
| | | | 2013 | 78 | 79 | 78 | 78 | 78 | 79 | 79 | 79 | 77 | 77 | 77 | 76 | 75 | 75 | 76 | 78 | 77 | 76 | 77 | 77 | 79 | 78 | 79 | 78 | 78 |
| Site 69 | Northeast | General Site | 2011 | 97 | 98 | 98 | 98 | 98 | 98 | 96 | 96 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 98 | 97 | 97 |
| | | | 2012 | 98 | 99 | 98 | 99 | 99 | 98 | 96 | 95 | 97 | 97 | 98 | 98 | 98 | 98 | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 |
| | | | 2013 | 62 | 61 | 62 | 62 | 62 | 62 | 62 | 62 | 62 | 62 | 60 | 61 | 61 | 61 | 61 | 61 | 61 | 62 | 62 | 61 | 62 | 62 | 62 | 62 | 62 |
| | | | 2014 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 90 | 89 | 90 | 90 | 90 | 89 | 90 | 89 |
| | | | 2015 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 79 | 80 | 81 | 81 | 81 | 81 | 81 | 80 | 81 | 80 | 81 | 81 | 81 | 81 | 81 | 81 |
| Site 71 | Northeast | | 2011 | 39 | 38 | 39 | 40 | 39 | 39 | 40 | 37 | 39 | 39 | 39 | 38 | 39 | 36 | 37 | 36 | 39 | 38 | 39 | 38 | 37 | 39 | 41 | 39 | 41 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | General Site | 2012 | 74 | 74 | 74 | 74 | 73 | 74 | 74 | 74 | 75 | 74 | 72 | 72 | 73 | 72 | 73 | 73 | 72 | 73 | 73 | 73 | 74 | 74 | 74 | 74 | 74 |
| | | | 2013 | 66 | 68 | 67 | 66 | 67 | 65 | 65 | 65 | 65 | 67 | 65 | 63 | 64 | 66 | 66 | 65 | 64 | 64 | 66 | 67 | 67 | 69 | 69 | 69 | 68 |
| | | | 2014 | 52 | 53 | 53 | 53 | 52 | 53 | 52 | 52 | 52 | 53 | 53 | 53 | 51 | 50 | 48 | 47 | 48 | 49 | 50 | 52 | 52 | 53 | 52 | 53 | 53 |
| | | | 2015 | 88 | 88 | 88 | 88 | 88 | 88 | 87 | 88 | 88 | 88 | 88 | 87 | 88 | 87 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 |
| Site 72 | South | General Site | 2011 | 86 | 87 | 88 | 87 | 87 | 87 | 86 | 86 | 84 | 84 | 85 | 84 | 85 | 84 | 84 | 85 | 85 | 85 | 86 | 86 | 85 | 86 | 86 | 86 | 87 |
| | | | 2012 | 87 | 86 | 86 | 85 | 86 | 86 | 87 | 88 | 87 | 86 | 86 | 86 | 87 | 88 | 88 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 87 | 87 | 85 |
| | | | 2013 | 92 | 93 | 93 | 93 | 93 | 92 | 92 | 92 | 92 | 91 | 91 | 91 | 92 | 91 | 91 | 91 | 92 | 92 | 91 | 92 | 92 | 93 | 93 | 93 | 93 |
| | | | 2014 | 94 | 95 | 95 | 96 | 95 | 95 | 95 | 94 | 93 | 93 | 93 | 93 | 93 | 93 | 93 | 94 | 94 | 94 | 94 | 94 | 95 | 96 | 96 | 95 | 95 |
| | | | 2015 | 99 | 99 | 99 | 99 | 99 | 100 | 100 | 99 | 99 | 99 | 97 | 98 | 98 | 98 | 99 | 99 | 99 | 98 | 98 | 99 | 99 | 99 | 99 | 99 | 99 |
| Site 73 | South | General Site | 2011 | 86 | 87 | 88 | 87 | 87 | 88 | 87 | 87 | 87 | 86 | 85 | 85 | 84 | 83 | 84 | 84 | 84 | 86 | 87 | 87 | 88 | 88 | 88 | 88 | 88 |
| | | | 2012 | 92 | 92 | 91 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 91 | 90 | 90 | 92 | 91 | 92 | 92 | 92 | 93 | 93 | 92 | 93 | 93 | 93 | 92 |
| | | | 2013 | 96 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 96 | 95 | 95 | 94 | 95 | 94 | 94 | 94 | 94 | 95 | 97 | 97 | 96 | 96 | 97 | 97 |
| | | | 2014 | 90 | 91 | 92 | 91 | 91 | 89 | 88 | 88 | 91 | 90 | 90 | 90 | 91 | 89 | 90 | 90 | 90 | 90 | 91 | 90 | 90 | 90 | 90 | 92 | 91 |
| | | | 2015 | 72 | 75 | 74 | 74 | 72 | 72 | 73 | 71 | 71 | 70 | 69 | 68 | 70 | 70 | 70 | 73 | 71 | 71 | 70 | 73 | 75 | 75 | 71 | 75 | 75 |
| Site 74 | South | General Site | 2011 | 81 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 78 | 78 | 78 | 80 | 83 | 83 | 82 | 82 | 83 | 82 | 83 | 83 | 82 | 82 | 82 | 81 | 80 |
| | | | 2012 | 81 | 82 | 82 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 80 | 80 | 80 | 81 | 81 | 82 | 82 | 82 | 82 | 82 | 82 | 81 | 82 |
| | | | 2013 | 91 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 91 | 92 | 92 | 92 | 92 | 91 | 91 | 91 | 90 | 91 | 91 | 91 | 91 | 91 | 92 | 92 |
| | | | 2014 | 80 | 80 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 81 | 80 | 80 | 81 | 80 | 80 | 80 | 81 | 80 | 81 | 80 | 78 | 79 | 79 | 80 | 80 |
| | | | 2015 | 94 | 93 | 93 | 93 | 94 | 93 | 94 | 93 | 94 | 94 | 94 | 94 | 94 | 93 | 93 | 94 | 94 | 93 | 94 | 93 | 93 | 94 | 93 | 94 | 93 |
| Site 75 | South | General Site | 2011 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 87 | 88 | 88 | 87 | 87 | 87 | 87 | 87 | 87 | 88 | 88 | 88 | 88 | 88 |
| | | | 2012 | 93 | 92 | 93 | 92 | 92 | 93 | 92 | 92 | 92 | 92 | 91 | 91 | 92 | 93 | 93 | 93 | 93 | 93 | 93 | 94 | 92 | 93 | 93 | 94 | 93 |
| | | | 2013 | 88 | 89 | 89 | 89 | 88 | 89 | 89 | 89 | 88 | 89 | 88 | 86 | 85 | 86 | 86 | 87 | 86 | 87 | 87 | 86 | 87 | 88 | 89 | 88 | 88 |

| Site | Region | Category | Year | Annual Average | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2014 | 94 | 94 | 94 | 94 | 94 | 94 | 93 | 93 | 94 | 93 | 93 | 93 | 93 | 93 | 94 | 94 | 94 | 93 | 93 | 94 | 94 | 94 | 93 | 94 | 94 |
| | | | 2015 | 78 | 79 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 77 | 78 | 79 | 78 | 77 | 77 | 78 | 79 | 79 | 78 | 79 | 79 | 79 |
| Site 76 | South | General Site | 2013 | 88 | 87 | 88 | 89 | 89 | 88 | 89 | 88 | 88 | 88 | 87 | 88 | 89 | 89 | 89 | 89 | 89 | 89 | 89 | 88 | 89 | 89 | 88 | 88 | 88 |
| | | | 2014 | 89 | 89 | 88 | 89 | 88 | 88 | 88 | 87 | 88 | 88 | 88 | 88 | 89 | 89 | 89 | 88 | 89 | 88 | 88 | 88 | 88 | 89 | 89 | 90 | 90 |
| | | | 2015 | 62 | 62 | 62 | 62 | 62 | 61 | 62 | 61 | 61 | 62 | 61 | 61 | 63 | 62 | 61 | 62 | 62 | 63 | 64 | 62 | 63 | 63 | 62 | 62 | 63 |

# Chapter 3

**Table S5:** Monthly contribution concentrations at monitoring sites across Northern Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Site 32 | North (Chiang Mai) | General Site | 2011 | Very Low | <5th Percentile | 9 | 1 | 1 | 1 | 10 | 3 | 12 | 26 | 21 | 16 | 8 | 1 | 1 | 0.5 |
| | | | | Low | <25th Percentile | 18 | 8 | 1 | 1 | 6 | 3 | 13 | 20 | 17 | 16 | 13 | 5 | 4 | 0.5 |
| | | | | Moderate | 25th-75th Percentile | 18-43 | 36 | 10 | 6 | 6 | 7 | 10 | 8 | 6 | 8 | 8 | 11 | 11 | 10 |
| | | | | High | >75th Percentile | 43 | 43 | 17 | 25 | 24 | 16 | 1 | 1 | 1 | 0.1 | 0.1 | 2 | 3 | 11 |
| | | | | Very High | >95th Percentile | 77 | 13 | 18 | 30 | 26 | 18 | 0.1 | - | 1 | - | - | - | 1 | 7 |
| | | | 2012 | Very Low | <5th Percentile | 12 | 1 | 2 | - | 1 | 3 | 23 | 15 | 11 | 11 | 28 | 4 | 3 | 1 |
| | | | | Low | <25th Percentile | 20 | 6 | 3 | 0.1 | 1 | 2 | 16 | 13 | 14 | 14 | 23 | 5 | 7 | 3 |
| | | | | Moderate | 25th-75th Percentile | 20-48 | 31 | 11 | 3 | 2 | 5 | 12 | 10 | 8 | 8 | 7 | 11 | 10 | 12 |
| | | | | High | >75th Percentile | 48 | 44 | 4 | 22 | 61 | 8 | 1 | 0.3 | 0.1 | 0.1 | 0.1 | 1 | 0.4 | 2 |
| | | | | Very High | >95th Percentile | 119 | 17 | 0.3 | 20 | 79 | 1 | - | - | - | - | - | - | - | 0.1 |
| | | | 2013 | Very Low | <5th Percentile | 8 | 0.4 | - | 3 | 1 | - | 2 | 18 | 10 | 19 | 16 | 15 | 10 | 6 |
| | | | | Low | <25th Percentile | 17 | 5 | 0.2 | 2 | 1 | 0.4 | 4 | 17 | 16 | 17 | 18 | 11 | 11 | 4 |
| | | | | Moderate | 25th-75th Percentile | 17-52 | 32 | 12 | 7 | 4 | 5 | 13 | 8 | 6 | 8 | 6 | 12 | 9 | 11 |
| | | | | High | >75th Percentile | 52 | 46 | 6 | 8 | 57 | 22 | 1 | 0.1 | - | - | - | 1 | 0.2 | 4 |
| | | | | Very High | >95th Percentile | 109 | 16 | 1 | 3 | 76 | - | 0.4 | - | - | - | - | 0.1 | - | 0.1 |
| | | | 2014 | Very Low | <5th Percentile | 10 | 1 | 0.2 | 1 | - | - | 4 | 18 | 22 | 22 | 20 | 5 | 7 | 1 |
| | | | | Low | <25th Percentile | 20 | 6 | 0.2 | 2 | - | - | 5 | 17 | 20 | 21 | 18 | 7 | 8 | 2 |
| | | | | Moderate | 25th-75th Percentile | 20-56 | 32 | 12 | 8 | 2 | 6 | 12 | 8 | 7 | 6 | 7 | 11 | 10 | 12 |
| | | | | High | >75th Percentile | 56 | 46 | 8 | 8 | 60 | 19 | 1 | - | - | - | 0.1 | 1 | 1 | 3 |
| | | | | Very High | >95th Percentile | 123 | 16 | 4 | 4 | 75 | 17 | - | - | - | - | - | - | 0.3 | 0.4 |
| | | | 2015 | Very Low | <5th Percentile | 9 | 0.5 | 27 | - | 1 | 0.4 | 10 | 8 | 6 | 10 | 8 | 18 | 9 | 3 |
| | | | | Low | <25th Percentile | 18 | 6 | 14 | - | 0.5 | 1 | 7 | 11 | 11 | 13 | 11 | 15 | 12 | 4 |
| | | | | Moderate | 25th-75th Percentile | 18-52 | 29 | 11 | 5 | 5 | 8 | 10 | 8 | 8 | 8 | 9 | 9 | 8 | 12 |
| | | | | High | >75th Percentile | 52 | 47 | 5 | 13 | 63 | 12 | 4 | 0.2 | 0.1 | 0.1 | 0.1 | 0.2 | 0.4 | 1 |
| | | | | Very High | >95th Percentile | 119 | 18 | 1 | 8 | 81 | 8 | 2 | - | - | 0.1 | - | - | 0.1 | 0.2 |
| Site 33 | North (Chiang Mai) | General Sitesite | 2011 | Very Low | <5th Percentile | 10 | 1 | 0.2 | 1 | 20 | 2 | 8 | 21 | 19 | 10 | 12 | 4 | 1 | 1 |
| | | | | Low | <25th Percentile | 20 | 8 | 1 | 1 | 12 | 2 | 7 | 19 | 18 | 12 | 14 | 7 | 6 | 2 |
| | | | | Moderate | 25th-75th Percentile | 20-46 | 38 | 9 | 6 | 7 | 7 | 8 | 7 | 7 | 9 | 8 | 11 | 8 | 12 |
| | | | | High | >75th Percentile | 46 | 41 | 16 | 21 | 27 | 22 | 6 | 1 | 0.4 | 1 | 0.2 | 2 | 1 | 4 |
| | | | | Very High | >95th Percentile | 80 | 12 | 15 | 22 | 32 | 25 | 5 | 0.1 | - | - | - | 0.1 | 0.1 | 2 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | 2013 | Very Low | <5th Percentile | 9 | 0.4 | 0.3 | - | 1 | 1 | 2 | 16 | 15 | 17 | 29 | 15 | 3 | - |
| | | | | Low | <25th Percentile | 20 | 6 | 0.4 | 0.3 | 1 | 1 | 6 | 16 | 18 | 16 | 23 | 11 | 6 | 0.3 |
| | | | | Moderate | 25th-75th Percentile | 20-59 | 32 | 12 | 7 | 5 | 5 | 11 | 6 | 6 | 7 | 6 | 12 | 11 | 12 |
| | | | | High | >75th Percentile | 59 | 46 | 6 | 10 | 51 | 26 | 1 | 0.3 | 0.1 | - | 0.3 | 1 | 1 | 3 |
| | | | | Very High | >95th Percentile | 131 | 16 | 1 | 3 | 69 | 27 | - | - | - | - | 0.3 | - | 0.2 | 0.1 |
| | | | 2015 | Very Low | <5th Percentile | 12 | 1 | 6 | - | - | 5 | 15 | 22 | 13 | 11 | 12 | 8 | 5 | 4 |
| | | | | Low | <25th Percentile | 23 | 6 | 5 | - | 0.3 | 5 | 11 | 20 | 14 | 12 | 11 | 10 | 7 | 4 |
| | | | | Moderate | 25th-75th Percentile | 23-61 | 32 | 10 | 5 | 5 | 6 | 10 | 5 | 8 | 8 | 10 | 9 | 10 | 13 |
| | | | | High | >75th Percentile | 61 | 45 | 4 | 11 | 68 | 10 | 3 | - | 0.1 | 0.3 | 0.1 | 1 | 1 | 2 |
| | | | | Very High | >95th Percentile | 124 | 16 | 0.4 | 4 | 88 | 6 | 1 | - | - | 0.1 | - | 0.2 | 1 | 0.3 |
| Site 30 | North (Chiang Rai) | General site | 2011 | Very Low | <5th Percentile | 12 | 1 | 1 | - | 6 | - | 7 | 12 | 11 | 28 | 21 | 9 | 5 | 0.4 |
| | | | | Low | <25th Percentile | 22 | 8 | 1 | 0.1 | 5 | 1 | 7 | 13 | 14 | 25 | 19 | 9 | 5 | 1 |
| | | | | Moderate | 25th-75th Percentile | 22-52 | 39 | 11 | 8 | 5 | 8 | 11 | 9 | 8 | 5 | 7 | 9 | 10 | 10 |
| | | | | High | >75th Percentile | 52 | 41 | 10 | 16 | 22 | 30 | 4 | 0.3 | 0.2 | 0.1 | 0.2 | 1 | 6 | 10 |
| | | | | Very High | >95th Percentile | 86 | 12 | 9 | 15 | 22 | 37 | 3 | - | 0.1 | - | 0.1 | 0.2 | 5 | 8 |
| | | | 2012 | Very Low | <5th Percentile | 11 | 0.5 | 1 | - | - | 1 | 9 | 7 | 16 | 24 | 23 | 10 | 7 | 2 |
| | | | | Low | <25th Percentile | 22 | 5 | 2 | - | - | 1 | 8 | 10 | 17 | 22 | 20 | 9 | 9 | 3 |
| | | | | Moderate | 25th-75th Percentile | 22-60 | 28 | 14 | 5 | 2 | 6 | 12 | 9 | 4 | 6 | 6 | 10 | 10 | 14 |
| | | | | High | >75th Percentile | 60 | 48 | 3 | 25 | 58 | 10 | 1 | 0.2 | - | - | 0.1 | 1 | 1 | 2 |
| | | | | Very High | >95th Percentile | 177 | 19 | - | 20 | 80 | - | - | - | - | - | - | - | - | - |
| | | | 2014 | Very Low | <5th Percentile | 7 | 0.4 | 1 | 0.4 | - | 1 | 6 | 16 | 18 | 34 | 14 | 4 | 6 | 1 |
| | | | | Low | <25th Percentile | 18 | 5 | 1 | 1 | - | 1 | 10 | 16 | 19 | 26 | 14 | 5 | 8 | 1 |
| | | | | Moderate | 25th-75th Percentile | 18-55 | 32 | 9 | 10 | 2 | 7 | 10 | 8 | 6 | 4 | 8 | 12 | 11 | 13 |
| | | | | High | >75th Percentile | 55 | 46 | 10 | 4 | 61 | 20 | 0.4 | 0.2 | 0.1 | 0.1 | 0.2 | 2 | 0.2 | 2 |
| | | | | Very High | >95th Percentile | 124 | 17 | 3 | 0.1 | 76 | 21 | - | - | - | - | - | - | - | - |
| Site 46 | North (Lamphun) | General Site | 2011 | Very Low | <5th Percentile | 7 | 0.5 | - | 0.2 | 8 | 0.2 | 13 | 20 | 18 | 16 | 18 | 5 | 0.3 | - |
| | | | | Low | <25th Percentile | 17 | 6 | 0.2 | 0.2 | 5 | 2 | 14 | 19 | 19 | 16 | 19 | 6 | 1 | 0.1 |
| | | | | Moderate | 25th-75th Percentile | 17-50 | 36 | 10 | 6 | 8 | 10 | 8 | 6 | 6 | 8 | 6 | 12 | 13 | 8 |
| | | | | High | >75th Percentile | 50 | 44 | 9 | 33 | 20 | 10 | 1 | 0.1 | 0.1 | 0.3 | 0.1 | 1 | 7 | 19 |
| | | | | Very High | >95th Percentile | 89 | 13 | 5 | 39 | 21 | 9 | - | - | - | 0.3 | - | 1 | 7 | 18 |
| | | | 2012 | Very Low | <5th Percentile | 7 | 0.3 | - | - | - | - | 7 | 18 | 21 | 23 | 24 | 3 | 2 | 2 |
| | | | | Low | <25th Percentile | 18 | 5 | 0.2 | - | 0.1 | 1 | 9 | 16 | 20 | 20 | 19 | 5 | 6 | 2 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 18-57 | 30 | 11 | 3 | 3 | 11 | 11 | 8 | 5 | 6 | 6 | 12 | 9 | 14 |
| | | | | High | $>75^{th}$ Percentile | 57 | 48 | 8 | 43 | 39 | 6 | 0.2 | 0.2 | - | - | 0.1 | 0.4 | 0.3 | 3 |
| | | | | Very High | $>95^{th}$ Percentile | 141 | 17 | 1 | 53 | 45 | 1 | - | - | - | - | - | - | - | 0.2 |
| | | | 2013 | Very Low | $<5^{th}$ Percentile | 6 | 0.3 | - | - | 2 | 1 | 4 | 16 | 21 | 16 | 29 | 9 | 1 | 1 |
| | | | | Low | $<25^{th}$ Percentile | 18 | 5 | 0.5 | 0.3 | 1 | 1 | 8 | 17 | 22 | 16 | 20 | 8 | 5 | 1 |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 18-58 | 34 | 11 | 7 | 4 | 7 | 10 | 6 | 5 | 8 | 6 | 11 | 12 | 11 |
| | | | | High | $>75^{th}$ Percentile | 58 | 46 | 8 | 11 | 60 | 12 | 1 | 0.2 | - | 0.2 | 0.2 | 1 | 0.3 | 6 |
| | | | | Very High | $>95^{th}$ Percentile | 116 | 15 | 4 | 5 | 82 | 6 | 0.1 | 0.2 | - | - | - | 0.2 | - | 2 |
| | | | 2014 | Very Low | $<5^{th}$ Percentile | 7 | 0.3 | - | 0.2 | - | - | 11 | 20 | 22 | 19 | 21 | 4 | 3 | - |
| | | | | Low | $<25^{th}$ Percentile | 18 | 5 | 0.1 | 0.3 | - | 0.3 | 11 | 20 | 21 | 18 | 19 | 5 | 4 | - |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 18-60 | 35 | 8 | 6 | 2 | 11 | 9 | 6 | 6 | 6 | 6 | 13 | 12 | 14 |
| | | | | High | $>75^{th}$ Percentile | 60 | 46 | 12 | 12 | 52 | 14 | 0.3 | 0.1 | - | - | - | 1 | 4 | 5 |
| | | | | Very High | $>95^{th}$ Percentile | 115 | 14 | 6 | 7 | 66 | 15 | - | - | - | - | - | 0.5 | 4 | 2 |

**Table S6:** Country contribution concentrations at monitoring sites across Northern Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Bangladesh | Cambodia | China | India | Laos | Marine | Myanmar | Thailand | Vietnam |
| Site 32 | North (Chiang Mai) | General Site | 2011 | Very Low | <5th Percentile | 9 | 1 | - | - | 4 | 0.2 | 3 | 34 | 12 | 46 | 1 |
| | | | | Low | <25th Percentile | 18 | 8 | - | - | 3 | 0.2 | 5 | 30 | 12 | 47 | 2 |
| | | | | Moderate | 25th-75th Percentile | 18-43 | 36 | 0.2 | - | 3 | 0.1 | 12 | 17 | 12 | 52 | 4 |
| | | | | High | >75th Percentile | 43 | 43 | 1 | - | 2 | 0.2 | 7 | 21 | 24 | 43 | 2 |
| | | | | Very High | >95th Percentile | 77 | 13 | 1 | 0.1 | 1 | 0.3 | 3 | 24 | 29 | 40 | 1 |
| | | | 2012 | Very Low | <5th Percentile | 12 | 1 | - | 1 | 3 | 0.3 | 8 | 27 | 10 | 49 | 2 |
| | | | | Low | <25th Percentile | 20 | 6 | 0.1 | 0.3 | 1 | 0.2 | 6 | 29 | 13 | 48 | 2 |
| | | | | Moderate | 25th-75th Percentile | 20-48 | 31 | 0.2 | - | - | - | 6 | 21 | 17 | 54 | 1 |
| | | | | High | >75th Percentile | 48 | 44 | 1 | - | - | - | 1 | 24 | 35 | 39 | 0.3 |
| | | | | Very High | >95th Percentile | 119 | 17 | 1 | - | - | - | - | 25 | 42 | 32 | - |
| | | | 2013 | Very Low | <5th Percentile | 8 | 0.4 | - | - | 8 | 0.1 | 10 | 20 | 13 | 43 | 6 |
| | | | | Low | <25th Percentile | 17 | 5 | - | - | 5 | 0.1 | 10 | 23 | 13 | 44 | 4 |
| | | | | Moderate | 25th-75th Percentile | 17-52 | 32 | - | - | 3 | 0.1 | 11 | 16 | 14 | 52 | 4 |
| | | | | High | >75th Percentile | 52 | 46 | 0.1 | 0.1 | - | - | 2 | 36 | 27 | 34 | 1 |
| | | | | Very High | >95th Percentile | 109 | 16 | - | 0.1 | - | - | - | 42 | 31 | 27 | - |
| | | | 2014 | Very Low | <5th Percentile | 10 | 1 | 0.1 | - | - | - | 2 | 31 | 21 | 47 | - |
| | | | | Low | <25th Percentile | 20 | 6 | 0.2 | - | - | - | 3 | 30 | 20 | 46 | 0.2 |
| | | | | Moderate | 25th-75th Percentile | 20-56 | 32 | 0.4 | - | 2 | 0.1 | 11 | 16 | 16 | 51 | 4 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Bangladesh | Cambodia | China | India | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | 56 | 46 | 1 | - | 2 | 0.1 | 3 | 24 | 23 | 45 | 2 |
| | | | | Very High | >95th Percentile | 123 | 16 | 1 | - | 1 | - | 1 | 25 | 25 | 47 | 0.5 |
| | | | 2015 | Very Low | <5th Percentile | 9 | 0.5 | - | - | 12 | 0.1 | 15 | 15 | 11 | 38 | 8 |
| | | | | Low | <25th Percentile | 18 | 6 | - | - | 7 | 0.1 | 14 | 19 | 14 | 41 | 5 |
| | | | | Moderate | 25th-75th Percentile | 18-52 | 29 | - | 0.1 | 2 | 0.1 | 13 | 16 | 16 | 48 | 4 |
| | | | | High | >75th Percentile | 52 | 47 | 2 | - | - | - | 2 | 17 | 32 | 46 | 0.4 |
| | | | | Very High | >95th Percentile | 119 | 18 | 2 | - | - | - | 1 | 17 | 36 | 43 | 0.2 |
| Site 33 | North (Chiang Mai) | General Site | 2011 | Very Low | <5th Percentile | 10 | 1 | 0.1 | - | 8 | 0.2 | 6 | 27 | 11 | 46 | 3 |
| | | | | Low | <25th Percentile | 20 | 8 | 0.1 | - | 5 | 0.2 | 7 | 27 | 12 | 46 | 3 |
| | | | | Moderate | 25th-75th Percentile | 20-46 | 38 | 0.2 | - | 2 | 0.1 | 12 | 18 | 11 | 52 | 4 |
| | | | | High | >75th Percentile | 46 | 41 | 1 | - | 1 | 0.1 | 4 | 23 | 25 | 46 | 1 |
| | | | | Very High | >95th Percentile | 80 | 12 | 1 | - | - | - | 1 | 26 | 30 | 41 | 0.2 |
| | | | 2013 | Very Low | <5th Percentile | 9 | 0.4 | - | - | 5 | 0.1 | 8 | 24 | 12 | 47 | 3 |
| | | | | Low | <25th Percentile | 20 | 6 | - | - | 3 | 0.1 | 8 | 26 | 13 | 47 | 3 |
| | | | | Moderate | 25th-75th Percentile | 20-59 | 32 | - | - | 3 | 0.1 | 13 | 15 | 13 | 52 | 5 |
| | | | | High | >75th Percentile | 59 | 46 | 0.1 | 0.1 | - | - | 2 | 37 | 25 | 35 | 1 |
| | | | | Very High | >95th Percentile | 131 | 16 | - | 0.2 | - | - | 0.1 | 44 | 28 | 27 | 0.1 |
| | | | 2015 | Very Low | <5th Percentile | 12 | 1 | - | - | 5 | 0.3 | 11 | 26 | 16 | 39 | 3 |
| | | | | Low | <25th Percentile | 23 | 6 | - | - | 4 | 0.2 | 11 | 25 | 16 | 41 | 3 |
| | | | | Moderate | 25th-75th Percentile | 23-61 | 32 | - | 0.1 | 2 | 0.1 | 13 | 16 | 16 | 48 | 4 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Bangladesh | Cambodia | China | India | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | 61 | 45 | 1 | - | - | - | 2 | 17 | 32 | 47 | 1 |
| | | | | Very High | >95th Percentile | 124 | 16 | 2 | - | - | - | 0.1 | 17 | 36 | 44 | 0.1 |
| Site 30 | North (Chiang Rai) | General site | 2011 | Very Low | <5th Percentile | 12 | 1 | - | 0.2 | 7 | 0.1 | 13 | 15 | 13 | 46 | 5 |
| | | | | Low | <25th Percentile | 22 | 8 | - | 0.1 | 6 | 0.1 | 13 | 16 | 13 | 46 | 5 |
| | | | | Moderate | 25th-75th Percentile | 22-52 | 39 | - | - | 7 | - | 22 | 9 | 12 | 41 | 9 |
| | | | | High | >75th Percentile | 52 | 41 | 0.2 | - | 5 | 0.1 | 13 | 11 | 13 | 51 | 6 |
| | | | | Very High | >95th Percentile | 86 | 12 | 0.1 | - | 4 | 0.1 | 11 | 12 | 13 | 55 | 5 |
| | | | 2012 | Very Low | <5th Percentile | 11 | 0.5 | - | - | 2 | 0.1 | 18 | 18 | 13 | 45 | 4 |
| | | | | Low | <25th Percentile | 22 | 5 | - | - | 1 | 0.1 | 15 | 19 | 14 | 46 | 3 |
| | | | | Moderate | 25th-75th Percentile | 22-60 | 28 | 0.1 | - | 2 | - | 14 | 11 | 15 | 54 | 4 |
| | | | | High | >75th Percentile | 60 | 48 | 1 | - | 1 | 0.2 | 5 | 16 | 34 | 42 | 1 |
| | | | | Very High | >95th Percentile | 177 | 19 | 1 | - | - | - | 2 | 21 | 45 | 31 | - |
| | | | 2014 | Very Low | <5th Percentile | 7 | 0.4 | - | - | - | - | 8 | 19 | 19 | 53 | 1 |
| | | | | Low | <25th Percentile | 18 | 5 | - | - | - | - | 9 | 18 | 19 | 52 | 1 |
| | | | | Moderate | 25th-75th Percentile | 18-55 | 32 | 0.3 | - | 3 | 0.1 | 19 | 9 | 16 | 47 | 5 |
| | | | | High | >75th Percentile | 55 | 46 | 1 | - | 2 | 0.1 | 10 | 16 | 23 | 45 | 4 |
| | | | | Very High | >95th Percentile | 124 | 17 | 0.2 | - | 1 | - | 8 | 17 | 25 | 47 | 2 |
| Site 46 | North (Lamphun) | General Site | 2011 | Very Low | <5th Percentile | 7 | 0.5 | - | - | 5 | 0.2 | 3 | 32 | 12 | 45 | 2 |
| | | | | Low | <25th Percentile | 17 | 6 | - | - | 3 | 0.2 | 3 | 33 | 13 | 45 | 2 |
| | | | | Moderate | 25th-75th Percentile | 17-50 | 36 | 0.1 | - | 3 | 0.1 | 12 | 16 | 10 | 54 | 4 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Bangladesh | Cambodia | China | India | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | 50 | 44 | 1 | - | 2 | 0.2 | 10 | 18 | 21 | 44 | 4 |
| | | | | Very High | >95th Percentile | 89 | 13 | 1 | - | 1 | 0.2 | 9 | 20 | 24 | 41 | 3 |
| | | | 2012 | Very Low | <5th Percentile | 7 | 0.3 | - | 0.1 | - | - | 4 | 42 | 14 | 38 | 1 |
| | | | | Low | <25th Percentile | 18 | 5 | - | 0.1 | - | - | 3 | 39 | 14 | 42 | 1 |
| | | | | Moderate | 25th-75th Percentile | 18-57 | 30 | 0.1 | - | - | - | 7 | 18 | 14 | 58 | 1 |
| | | | | High | >75th Percentile | 57 | 48 | 2 | - | - | - | 1 | 17 | 35 | 44 | 0.3 |
| | | | | Very High | >95th Percentile | 141 | 17 | 3 | - | - | 1 | 0.1 | 15 | 41 | 40 | - |
| | | | 2013 | Very Low | <5th Percentile | 6 | 0.3 | - | - | 2 | 0.1 | 5 | 32 | 14 | 45 | 1 |
| | | | | Low | <25th Percentile | 18 | 5 | - | - | 2 | 0.1 | 6 | 30 | 14 | 45 | 2 |
| | | | | Moderate | 25th-75th Percentile | 18-58 | 34 | - | - | 3 | - | 12 | 16 | 12 | 52 | 5 |
| | | | | High | >75th Percentile | 58 | 46 | - | - | - | - | 3 | 29 | 26 | 40 | 1 |
| | | | | Very High | >95th Percentile | 116 | 15 | - | 0.1 | - | - | 1 | 31 | 31 | 36 | 1 |
| | | | 2014 | Very Low | <5th Percentile | 7 | 0.3 | - | - | - | - | 2 | 34 | 17 | 46 | - |
| | | | | Low | <25th Percentile | 18 | 5 | - | - | - | - | 2 | 34 | 18 | 46 | 0.1 |
| | | | | Moderate | 25th-75th Percentile | 18-60 | 35 | 0.3 | - | 2 | 0.1 | 11 | 16 | 14 | 53 | 4 |
| | | | | High | >75th Percentile | 60 | 46 | 1 | 0.1 | 2 | - | 5 | 23 | 19 | 48 | 2 |
| | | | | Very High | >95th Percentile | 115 | 14 | 1 | 0.2 | 1 | - | 2 | 24 | 20 | 52 | 1 |

**Table S7:** Hourly contribution concentrations at monitoring sites across Northern Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| Site 32 | North (Chiang Mai) | General Site | 2011 | Very Low | <5th Percentile | 9 | 1 | 9 | 8 | 7 | 6 | 5 | 3 | 3 | 1 | 1 | 3 | 5 | 5 | 7 | 5 | 5 | 5 | 4 | 2 | 1 | 1 | 1 | 1 | 4 | 9 |
| | | | | Low | <25th Percentile | 18 | 8 | 7 | 7 | 6 | 6 | 5 | 4 | 2 | 1 | 2 | 4 | 5 | 5 | 6 | 5 | 5 | 5 | 4 | 2 | 2 | 1 | 2 | 2 | 4 | 6 |
| | | | | Moderate | 25th-75th Percentile | 18-43 | 36 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 43 | 43 | 1 | 1 | 2 | 1 | 1 | 1 | 4 | 7 | 9 | 4 | 4 | 2 | 2 | 2 | 2 | 3 | 3 | 7 | 15 | 12 | 9 | 5 | 2 | 1 |
| | | | | Very High | >95th Percentile | 77 | 13 | 0.4 | 1 | 2 | 1 | 1 | 0.2 | 4 | 6 | 10 | 5 | 4 | 2 | 1 | 1 | 2 | 2 | 2 | 7 | 19 | 14 | 10 | 5 | 2 | 1 |
| | | | 2012 | Very Low | <5th Percentile | 12 | 1 | 9 | 10 | 6 | 9 | 6 | 4 | 2 | 0.2 | 2 | 3 | 2 | 4 | 4 | 5 | 4 | 5 | 4 | 2 | 1 | 1 | 4 | 6 | 3 | 5 |
| | | | | Low | <25th Percentile | 20 | 6 | 8 | 9 | 7 | 8 | 7 | 5 | 2 | 1 | 2 | 3 | 3 | 3 | 4 | 5 | 4 | 5 | 4 | 2 | 2 | 2 | 3 | 4 | 3 | 6 |
| | | | | Moderate | 25th-75th Percentile | 20-48 | 31 | 3 | 3 | 3 | 3 | 3 | 4 | 5 | 6 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 48 | 44 | 3 | 2 | 2 | 3 | 3 | 4 | 5 | 5 | 8 | 6 | 7 | 5 | 6 | 4 | 3 | 3 | 2 | 4 | 5 | 6 | 4 | 4 | 3 | 3 |
| | | | | Very High | >95th Percentile | 119 | 17 | 3 | 2 | 2 | 3 | 2 | 4 | 5 | 5 | 8 | 7 | 9 | 6 | 7 | 5 | 2 | 2 | 2 | 3 | 4 | 5 | 4 | 3 | 3 | 2 |
| | | | 2013 | Very Low | <5th Percentile | 8 | 0.4 | 8 | 12 | 8 | 10 | 5 | 3 | 2 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 8 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 4 | 11 |
| | | | | Low | <25th Percentile | 17 | 5 | 7 | 9 | 7 | 8 | 6 | 4 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 6 | 4 | 3 | 2 | 1 | 2 | 2 | 3 | 4 | 8 |
| | | | | Moderate | 25th-75th Percentile | 17-52 | 32 | 4 | 4 | 4 | 3 | 3 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 52 | 46 | 2 | 2 | 3 | 3 | 4 | 4 | 6 | 7 | 9 | 7 | 8 | 6 | 4 | 3 | 2 | 2 | 2 | 4 | 4 | 4 | 5 | 4 | 4 | 2 |
| | | | | Very High | >95th Percentile | 109 | 16 | 2 | 2 | 3 | 3 | 4 | 5 | 7 | 8 | 10 | 9 | 10 | 8 | 5 | 3 | 1 | 2 | 1 | 3 | 2 | 2 | 3 | 3 | 3 | 2 |
| | | | 2014 | Very Low | <5th Percentile | 10 | 1 | 7 | 8 | 10 | 12 | 4 | 3 | 1 | 1 | 1 | 2 | 8 | 4 | 3 | 4 | 5 | 6 | 4 | 1 | 3 | 3 | 1 | 2 | 2 | 5 |
| | | | | Low | <25th Percentile | 20 | 6 | 7 | 7 | 8 | 9 | 6 | 4 | 2 | 2 | 2 | 3 | 6 | 4 | 3 | 4 | 4 | 5 | 3 | 2 | 3 | 2 | 2 | 3 | 4 | 6 |
| | | | | Moderate | 25th-75th Percentile | 20-56 | 32 | 4 | 4 | 4 | 3 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 3 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 56 | 46 | 2 | 2 | 2 | 2 | 2 | 3 | 5 | 8 | 11 | 8 | 6 | 7 | 4 | 4 | 3 | 2 | 4 | 4 | 5 | 4 | 5 | 4 | 2 | 2 |
| | | | | Very High | >95th Percentile | 123 | 16 | 2 | 2 | 2 | 2 | 2 | 3 | 5 | 9 | 14 | 9 | 8 | 8 | 5 | 4 | 2 | 1 | 3 | 4 | 4 | 3 | 3 | 3 | 2 | 2 |
| | | | 2015 | Very Low | <5th Percentile | 9 | 0.5 | 9 | 9 | 8 | 10 | 8 | 6 | 3 | 1 | 2 | 1 | 1 | 2 | 3 | 3 | 3 | 7 | 4 | 3 | 2 | 2 | 1 | 2 | 3 | 5 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| | | | | Low | <25th Percentile | 18 | 6 | 7 | 8 | 8 | 8 | 8 | 7 | 3 | 2 | 2 | 2 | 3 | 3 | 4 | 4 | 4 | 5 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 5 |
| | | | | Moderate | 25th-75th Percentile | 18-52 | 29 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 |
| | | | | High | >75th Percentile | 52 | 47 | 2 | 2 | 2 | 2 | 3 | 3 | 5 | 8 | 9 | 8 | 6 | 7 | 5 | 4 | 3 | 2 | 2 | 4 | 4 | 5 | 4 | 4 | 3 | 2 |
| | | | | Very High | >95th Percentile | 119 | 18 | 1 | 2 | 1 | 2 | 3 | 4 | 6 | 10 | 11 | 9 | 7 | 8 | 6 | 4 | 3 | 2 | 2 | 3 | 3 | 5 | 4 | 3 | 2 | 2 |
| Site 33 | North (Chiang Mai) | General Site | 2011 | Very Low | <5th Percentile | 10 | 1 | 10 | 8 | 10 | 8 | 9 | 3 | 2 | 1 | 1 | 1 | 3 | 4 | 8 | 6 | 4 | 5 | 2 | 1 | 1 | 1 | 1 | 2 | 4 | 7 |
| | | | | Low | <25th Percentile | 20 | 8 | 7 | 7 | 8 | 7 | 8 | 5 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 5 | 5 | 3 | 1 | 1 | 1 | 2 | 2 | 4 | 5 |
| | | | | Moderate | 25th-75th Percentile | 20-46 | 38 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 3 | 3 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 46 | 41 | 4 | 3 | 2 | 1 | 3 | 1 | 2 | 6 | 9 | 5 | 3 | 2 | 1 | 1 | 1 | 2 | 1 | 3 | 5 | 8 | 14 | 12 | 7 | 5 |
| | | | | Very High | >95th Percentile | 80 | 12 | 4 | 2 | 1 | 0.3 | 3 | 1 | 2 | 5 | 10 | 6 | 3 | 1 | 0.4 | 1 | 1 | 2 | 1 | 2 | 4 | 8 | 17 | 15 | 8 | 5 |
| | | | 2013 | Very Low | <5th Percentile | 9 | 0.4 | 11 | 9 | 11 | 13 | 9 | 7 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 4 | 2 | 3 | 2 | 1 | 0.2 | 1 | 0.3 | 2 | 5 | 9 |
| | | | | Low | <25th Percentile | 20 | 6 | 7 | 7 | 8 | 9 | 8 | 7 | 3 | 2 | 2 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 1 | 2 | 2 | 3 | 4 | 6 |
| | | | | Moderate | 25th-75th Percentile | 20-59 | 32 | 4 | 4 | 4 | 3 | 3 | 3 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 59 | 46 | 3 | 4 | 3 | 3 | 3 | 4 | 4 | 6 | 7 | 7 | 6 | 5 | 4 | 2 | 2 | 2 | 2 | 3 | 4 | 7 | 6 | 5 | 5 | 4 |
| | | | | Very High | >95th Percentile | 131 | 16 | 3 | 4 | 3 | 3 | 4 | 5 | 5 | 8 | 9 | 9 | 8 | 5 | 3 | 1 | 1 | 1 | 0.5 | 1 | 2 | 6 | 5 | 4 | 4 | 4 |
| | | | 2015 | Very Low | <5th Percentile | 12 | 1 | 12 | 5 | 5 | 17 | 11 | 6 | 4 | 4 | 7 | 3 | 2 | 1 | 2 | 1 | 4 | 2 | 4 | 1 | 0.2 | 0.4 | 1 | 2 | 1 | 3 |
| | | | | Low | <25th Percentile | 23 | 6 | 8 | 5 | 6 | 12 | 9 | 7 | 5 | 5 | 6 | 4 | 3 | 2 | 3 | 3 | 4 | 3 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 4 |
| | | | | Moderate | 25th-75th Percentile | 23-61 | 32 | 4 | 4 | 3 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 61 | 45 | 4 | 3 | 4 | 3 | 4 | 4 | 5 | 4 | 6 | 8 | 7 | 6 | 4 | 3 | 3 | 2 | 2 | 2 | 3 | 4 | 5 | 5 | 5 | 4 |
| | | | | Very High | >95th Percentile | 124 | 16 | 3 | 3 | 4 | 3 | 5 | 4 | 5 | 5 | 8 | 10 | 8 | 7 | 5 | 4 | 3 | 2 | 1 | 2 | 2 | 3 | 3 | 3 | 5 | 3 |
| Site 30 | North (Chiang Rai) | General Site | 2011 | Very Low | <5th Percentile | 12 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 17 | 13 | 10 | 8 | 9 | 9 | 8 | 6 | 2 | 0.4 | 0.3 | 0.4 | 1 | 1 | 1 | 1 |
| | | | | Low | <25th Percentile | 22 | 8 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 4 | 11 | 9 | 7 | 6 | 7 | 7 | 6 | 6 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| | | | | Moderate | 25th-75th Percentile | 22-52 | 39 | 4 | 4 | 5 | 4 | 4 | 5 | 5 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 52 | 41 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 6 | 14 | 15 | 8 | 6 | 4 | 3 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| | | | | Very High | >95$^{th}$ Percentile | 86 | 12 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 5 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 4 | 17 | 20 | 9 | 5 | 4 | 3 |
| | | | 2012 | Very Low | <5$^{th}$ Percentile | 11 | 0.5 | 2 | 2 | 2 | 2 | 1 | 3 | 1 | 3 | 17 | 16 | 11 | 5 | 4 | 5 | 5 | 6 | 4 | 1 | 0.3 | 1 | 1 | 2 | 3 | 2 |
| | | | | Low | <25$^{th}$ Percentile | 22 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 11 | 11 | 8 | 4 | 4 | 4 | 5 | 5 | 3 | 1 | 1 | 1 | 2 | 3 | 3 | 3 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 22-60 | 28 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 4 | 5 | 5 | 4 | 4 | 5 | 4 | 5 | 5 |
| | | | | High | >75$^{th}$ Percentile | 60 | 48 | 4 | 3 | 4 | 4 | 3 | 3 | 3 | 4 | 5 | 4 | 4 | 6 | 4 | 5 | 4 | 3 | 3 | 5 | 6 | 6 | 5 | 5 | 4 | 4 |
| | | | | Very High | >95$^{th}$ Percentile | 177 | 19 | 5 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 4 | 4 | 4 | 6 | 8 | 8 | 7 | 5 | 4 |
| | | | 2014 | Very Low | <5$^{th}$ Percentile | 7 | 0.4 | 7 | 6 | 4 | 4 | 3 | 3 | 2 | 3 | 9 | 7 | 4 | 3 | 6 | 2 | 5 | 5 | 3 | 3 | 3 | 3 | 4 | 5 | 4 | 4 |
| | | | | Low | <25$^{th}$ Percentile | 18 | 5 | 6 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 7 | 6 | 4 | 3 | 4 | 2 | 4 | 4 | 3 | 2 | 3 | 3 | 4 | 4 | 4 | 5 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 18-55 | 32 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 3 | 4 | 5 | 4 | 4 | 5 | 4 | 4 | 5 | 5 | 4 | 4 | 3 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | 55 | 46 | 3 | 5 | 4 | 4 | 3 | 3 | 5 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 3 | 3 | 3 | 3 | 7 | 6 | 5 | 5 | 4 | 3 |
| | | | | Very High | >95$^{th}$ Percentile | 124 | 17 | 3 | 5 | 5 | 4 | 4 | 4 | 6 | 5 | 4 | 5 | 5 | 5 | 5 | 3 | 2 | 3 | 2 | 2 | 6 | 5 | 4 | 5 | 4 | 3 |
| Site 46 | North (Lamphun) | General Site | 2011 | Very Low | <5$^{th}$ Percentile | 7 | 0.5 | 5 | 3 | 5 | 4 | 3 | 3 | 2 | 2 | 6 | 7 | 7 | 6 | 4 | 6 | 6 | 3 | 4 | 3 | 3 | 2 | 3 | 4 | 4 | 4 |
| | | | | Low | <25$^{th}$ Percentile | 17 | 6 | 4 | 4 | 5 | 4 | 4 | 4 | 3 | 4 | 5 | 5 | 6 | 5 | 5 | 5 | 6 | 4 | 4 | 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 17-50 | 36 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 3 | 4 | 4 | 4 | 5 | 5 | 4 | 5 | 5 | 5 | 3 | 3 | 3 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | 50 | 44 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 3 | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 11 | 17 | 14 | 5 | 5 | 3 |
| | | | | Very High | >95$^{th}$ Percentile | 89 | 13 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 3 | 0.5 | 13 | 22 | 19 | 5 | 5 | 1 |
| | | | 2012 | Very Low | <5$^{th}$ Percentile | 7 | 0.3 | 5 | 4 | 5 | 4 | 5 | 2 | 2 | 4 | 5 | 4 | 6 | 4 | 4 | 8 | 7 | 7 | 4 | 2 | 0.4 | 1 | 3 | 5 | 4 | 6 |
| | | | | Low | <25$^{th}$ Percentile | 18 | 5 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 6 | 6 | 5 | 4 | 3 | 1 | 2 | 3 | 3 | 4 | 5 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 18-57 | 30 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 5 | 4 | 5 | 4 | 4 | 4 | 4 | 6 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | 57 | 48 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 5 | 6 | 6 | 6 | 4 | 4 | 2 | 2 | 2 | 2 | 2 | 5 | 6 | 5 | 5 | 4 | 4 |
| | | | | Very High | >95$^{th}$ Percentile | 141 | 17 | 4 | 6 | 5 | 4 | 4 | 3 | 3 | 5 | 7 | 8 | 8 | 5 | 5 | 3 | 1 | 2 | 1 | 2 | 3 | 6 | 5 | 5 | 3 | 3 |
| | | | 2013 | Very Low | <5$^{th}$ Percentile | 6 | 0.3 | 7 | 3 | 5 | 5 | 5 | 2 | 3 | 4 | 8 | 6 | 5 | 4 | 4 | 6 | 5 | 3 | 4 | 3 | 1 | 3 | 1 | 3 | 3 | 6 |
| | | | | Low | <25$^{th}$ Percentile | 18 | 5 | 5 | 4 | 5 | 5 | 5 | 4 | 3 | 4 | 6 | 5 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 3 | 2 | 3 | 3 | 4 | 4 | 5 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 18-58 | 34 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >$75^{th}$ Percentile | 58 | 46 | 5 | 4 | 5 | 5 | 4 | 4 | 5 | 6 | 5 | 6 | 6 | 4 | 3 | 2 | 2 | 1 | 1 | 2 | 4 | 7 | 6 | 5 | 4 | 4 |
| | | | | Very High | >$95^{th}$ Percentile | 116 | 15 | 5 | 3 | 6 | 6 | 5 | 4 | 5 | 7 | 7 | 7 | 8 | 4 | 2 | 2 | 1 | 1 | 0.2 | 1 | 2 | 7 | 5 | 5 | 3 | 4 |
| | | | 2014 | Very Low | <$5^{th}$ Percentile | 7 | 0.3 | 5 | 3 | 4 | 4 | 3 | 3 | 2 | 4 | 12 | 7 | 6 | 3 | 4 | 3 | 3 | 4 | 2 | 3 | 1 | 2 | 4 | 6 | 7 | 8 |
| | | | | Low | <$25^{th}$ Percentile | 18 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 3 | 4 | 8 | 6 | 5 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 4 | 5 | 5 | 6 |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 18-60 | 35 | 7 | 7 | 7 | 7 | 7 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 1 | 1 | 1 | 1 | 0.3 |
| | | | | High | >$75^{th}$ Percentile | 60 | 46 | 8 | 8 | 8 | 7 | 7 | 7 | 6 | 6 | 6 | 5 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | 1 | 0.5 | 0.2 |
| | | | | Very High | >$95^{th}$ Percentile | 115 | 14 | 9 | 8 | 8 | 8 | 7 | 7 | 7 | 6 | 6 | 5 | 4 | 4 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 0.2 | 0.1 |

**Table S8:** Monthly contribution concentrations at monitoring sites across Southern Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 72 | South (Narathiwat) | General Site | 2015 | Very Low | <5th Percentile | 9 | 1 | 4 | - | - | 6 | 12 | 4 | 11 | 13 | 17 | 17 | 16 | 0.4 |
| | | | | Low | <25th Percentile | 18 | 8 | 3 | 1 | 1 | 5 | 11 | 5 | 13 | 16 | 13 | 13 | 16 | 2 |
| | | | | Moderate | 25th-75th Percentile | 18-40 | 37 | 9 | 10 | 11 | 12 | 9 | 8 | 8 | 7 | 6 | 5 | 7 | 8 |
| | | | | High | >75th Percentile | 40 | 41 | 6 | 4 | 4 | 2 | 6 | 7 | 1 | 2 | 14 | 41 | 1 | 14 |
| | | | | Very High | >95th Percentile | 70 | 13 | 2 | 2 | 2 | 1 | 6 | 5 | 0.2 | 1 | 15 | 52 | 0.2 | 14 |
| 73 | South (Phuket) | General Site | 2013 | Very Low | <5th Percentile | 8 | 1 | 0.2 | 1 | 3 | 22 | 12 | 14 | 2 | 3 | 19 | 11 | 14 | - |
| | | | | Low | <25th Percentile | 15 | 9 | 2 | 2 | 3 | 16 | 13 | 11 | 4 | 6 | 16 | 14 | 14 | 1 |
| | | | | Moderate | 25th-75th Percentile | 15-30 | 40 | 9 | 9 | 6 | 8 | 10 | 6 | 10 | 12 | 10 | 8 | 7 | 5 |
| | | | | High | >75th Percentile | 30 | 39 | 9 | 14 | 11 | 3 | 1 | 26 | 4 | 3 | 0.3 | 8 | 2 | 18 |
| | | | | Very High | >95th Percentile | 45 | 11 | 8 | 15 | 11 | 1 | 0.1 | 31 | 2 | 2 | - | 11 | 2 | 17 |
| 75 | South (Songkhla) | General Site | 2014 | Very Low | <5th Percentile | 20 | 2 | - | - | 1 | 15 | 3 | 1 | 1 | 10 | 22 | 16 | 21 | 11 |
| | | | | Low | <25th Percentile | 32 | 12 | 0.5 | 1 | 3 | 10 | 6 | 2 | 2 | 11 | 18 | 15 | 18 | 12 |
| | | | | Moderate | 25th-75th Percentile | 32-52 | 41 | 8 | 10 | 12 | 8 | 9 | 6 | 9 | 7 | 7 | 8 | 4 | 10 |
| | | | | High | >75th Percentile | 52 | 36 | 9 | 8 | 3 | 5 | 5 | 22 | 24 | 7 | 4 | 3 | 3 | 5 |
| | | | | Very High | >95th Percentile | 75 | 10 | 7 | 9 | 1 | 4 | 4 | 25 | 30 | 6 | 3 | 3 | 3 | 6 |

**Table S9:** Country contribution concentrations at monitoring sites across Southern Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Cambodia | China | India | Indonesia | Laos | Malaysia | Marine | Myanmar | Philippines | Taiwan | Thailand | Vietnam |
| 72 | South (Narathiwat) | General Site | 2015 | Very Low | <5th Percentile | 9 | 1 | 1 | - | - | 1 | - | 26 | 59 | - | 0.3 | - | 13 | 0.3 |
| | | | | Low | <25th Percentile | 18 | 8 | 1 | 0.1 | - | 1 | - | 26 | 57 | - | 0.2 | - | 14 | 0.4 |
| | | | | Moderate | 25th-75th Percentile | 18-40 | 37 | 0.4 | 0.2 | - | 1 | 0.1 | 22 | 64 | - | 0.1 | 0.1 | 11 | 1 |
| | | | | High | >75th Percentile | 40 | 41 | 0.4 | 0.1 | - | 1 | 0.1 | 39 | 43 | - | 0.2 | - | 15 | 1 |
| | | | | Very High | >95th Percentile | 70 | 13 | 0.2 | - | - | 1 | - | 46 | 36 | - | 0.1 | 0.1 | 16 | 0.5 |
| 73 | South (Phuket) | General Site | 2013 | Very Low | <5th Percentile | 8 | 1 | 2 | 0.1 | 0.2 | 0.5 | 0.2 | 1 | 86 | - | - | - | 10 | 1 |
| | | | | Low | <25th Percentile | 15 | 9 | 2 | 0.2 | 0.1 | 1 | 0.3 | 1 | 85 | - | - | - | 10 | 1 |
| | | | | Moderate | 25th-75th Percentile | 15-30 | 40 | 2 | 0.2 | 0.1 | 2 | 0.3 | 1 | 83 | 0.4 | - | - | 10 | 2 |
| | | | | High | >75th Percentile | 30 | 39 | 3 | 1 | 0.1 | 0.4 | 1 | 0.1 | 74 | 0.2 | - | - | 18 | 3 |
| | | | | Very High | >95th Percentile | 45 | 11 | 2 | 0.5 | - | 0.2 | 2 | 0.1 | 74 | 0.1 | - | - | 18 | 2 |
| 75 | South (Songkhla) | General Site | 2014 | Very Low | <5th Percentile | 20 | 2 | 2 | 1 | 0.1 | 1 | 0.4 | 2 | 69 | - | - | - | 20 | 4 |
| | | | | Low | <25th Percentile | 32 | 12 | 2 | 1 | 0.1 | 1 | 1 | 4 | 69 | - | - | - | 18 | 3 |
| | | | | Moderate | 25th-75th Percentile | 32-52 | 41 | 2 | 1 | - | 1 | 1 | 7 | 69 | - | - | - | 16 | 3 |
| | | | | High | >75th Percentile | 52 | 36 | 2 | 0.3 | - | 1 | 1 | 23 | 52 | - | - | - | 18 | 2 |
| | | | | Very High | >95th Percentile | 75 | 10 | 2 | 0.2 | - | 1 | 1 | 28 | 48 | - | - | - | 18 | 2 |

**Table S10:** Hourly contribution concentrations at monitoring sites across Southern Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| 72 | South (Narathiwat) | General Site | 2015 | Very Low | <5th Percentile | 9 | 1 | 8 | 6 | 7 | 7 | 7 | 5 | 4 | 5 | 4 | 1 | 3 | 2 | 3 | 6 | 5 | 5 | 3 | 4 | 1 | 1 | 1 | 4 | 3 | 4 |
| | | | | Low | <25th Percentile | 18 | 8 | 6 | 6 | 6 | 7 | 7 | 6 | 5 | 4 | 3 | 2 | 3 | 2 | 3 | 5 | 5 | 5 | 4 | 4 | 2 | 2 | 2 | 3 | 3 | 4 |
| | | | | Moderate | 25th-75th Percentile | 18-40 | 37 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 40 | 41 | 4 | 5 | 4 | 5 | 2 | 2 | 2 | 3 | 5 | 6 | 5 | 5 | 4 | 4 | 3 | 4 | 3 | 5 | 4 | 4 | 4 | 6 | 5 | 4 |
| | | | | Very High | >95th Percentile | 70 | 13 | 4 | 6 | 4 | 6 | 2 | 2 | 2 | 3 | 5 | 6 | 4 | 5 | 4 | 4 | 3 | 4 | 3 | 5 | 4 | 3 | 4 | 6 | 5 | 4 |
| 73 | South (Phuket) | General Site | 2013 | Very Low | <5th Percentile | 8 | 1 | 2 | 3 | 5 | 10 | 8 | 6 | 4 | 6 | 4 | 3 | 3 | 1 | 2 | 4 | 8 | 10 | 9 | 2 | 1 | 1 | 2 | 2 | 3 | 2 |
| | | | | Low | <25th Percentile | 15 | 9 | 2 | 4 | 5 | 8 | 7 | 6 | 4 | 4 | 3 | 3 | 4 | 2 | 3 | 4 | 7 | 8 | 7 | 3 | 2 | 2 | 2 | 3 | 3 | 2 |
| | | | | Moderate | 25th-75th Percentile | 15-30 | 40 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | 30 | 39 | 3 | 4 | 3 | 2 | 2 | 1 | 9 | 4 | 6 | 5 | 5 | 5 | 5 | 4 | 4 | 2 | 2 | 3 | 4 | 5 | 7 | 6 | 6 | 4 |
| | | | | Very High | >95th Percentile | 45 | 11 | 2 | 5 | 3 | 2 | 2 | 1 | 11 | 3 | 6 | 4 | 5 | 6 | 6 | 4 | 5 | 1 | 2 | 2 | 4 | 5 | 7 | 7 | 6 | 3 |
| 75 | South (Songkhla) | General Site | 2014 | Very Low | <5th Percentile | 20 | 2 | 3 | 3 | 3 | 4 | 7 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 9 | 7 | 6 | 7 | 11 | 4 | 5 | 11 | 1 | 4 | 2 |
| | | | | Low | <25th Percentile | 32 | 12 | 3 | 3 | 4 | 4 | 6 | 3 | 2 | 2 | 1 | 2 | 2 | 3 | 4 | 8 | 6 | 6 | 7 | 9 | 5 | 4 | 7 | 2 | 3 | 3 |
| | | | | Moderate | 25th-75th Percentile | 32-52 | 41 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 5 | 4 |
| | | | | High | >75th Percentile | 52 | 36 | 5 | 7 | 5 | 4 | 4 | 5 | 4 | 6 | 12 | 9 | 4 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 3 | 4 | 5 | 4 | 4 |
| | | | | Very High | >95th Percentile | 75 | 10 | 6 | 8 | 5 | 5 | 4 | 6 | 4 | 6 | 14 | 9 | 4 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 3 | 4 | 5 | 4 | 3 |

# Chapter 4

**Table S11:** Number of sites and years across central Thailand with sufficient data capture above 75% of hourly observations across the year, for each month, and for each hour of the day between 2011 and 2015

| Category | Region | Province | Site | Year |
|---|---|---|---|---|
| Roadside site | Central | Bangkok | Site 12 | 2011 |
| | | | | 2013 |
| | | | Site 14 | 2015 |
| | | | Site 15 | 2014 |
| | | | Site 16 | 2013 |
| | | | | 2015 |
| | | **Total** | **4** | **6** |
| General Site | Central | Bangkok | Site 2 | 2014 |
| | | | Site 6 | 2012 |
| | | | | 2014 |
| | | | | 2015 |
| | | | Site 7 | 2012 |
| | | | Site 8 | 2014 |
| | | | Site 9 | 2013 |
| | | | Site 17 | 2015 |
| | | | Site 18 | 2013 |
| | | | | 2014 |
| | | Total | 7 | 10 |
| | | Nonthaburi | Site 19 | 2012 |
| | | | Site 20 | 2011 |
| | | Pathumthani | Site 21 | 2013 |
| | | | | 2014 |
| | | Samut Prakan | Site 22 | 2012 |
| | | | Site 23 | 2013 |
| | | | | 2014 |
| | | | Site 24 | 2012 |
| | | | | 2013 |
| | | | | 2014 |
| | | | | 2015 |
| | | | Site 25 | 2012 |
| | | | | 2013 |
| | | | Site 26 | 2013 |
| | | | | 2014 |
| | | Samut Sakhon | Site 27 | 2014 |
| | | | Site 28 | 2014 |
| | | Ratchaburi | Site 47 | 2015 |
| | | Saraburi | Site 49 | 2011 |
| | | | | 2012 |
| | | | | 2014 |
| | | | | 2015 |
| | | Phra Nakhon Si Ayutthaya | Site 51 | 2014 |
| | | **Total** | **13** | **23** |
| **Total** | | **8 provinces** | **24** | **39** |

**Table S12:** Annual average $PM_{10}$ concentrations (µg $m^{-3}$) at monitoring sites across central Thailand for annual $PM_{10}$ concentrations between 2011 and 2015

| Site | Category | Region | Province | 2011 | 2012 | 2013 | 2014 | 2015 | Annual average $PM_{10}$ concentrations (µg $m^{-3}$) | Level |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | General Site | Central | Bangkok | - | 37.2 | 41.3 | 36.8 | - | 38.4 | Moderate |
| 2 | General Site | Central | Bangkok | - | - | 52.7 | 51.4 | 42.0 | 48.7 | Moderate |
| 6 | General Site | Central | Bangkok | 28.0 | 25.8 | - | 47.0 | 39.8 | 35.2 | Moderate |
| 7 | General Site | Central | Bangkok | 40.4 | 43.9 | 42.1 | 40.4 | 33.7 | 40.1 | Moderate |
| 8 | General Site | Central | Bangkok | - | - | 49.7 | 48.2 | 44.7 | 47.5 | Moderate |
| 9 | General Site | Central | Bangkok | - | - | 20.2 | 17.0 | 20.8 | 19.3 | Low |
| 18 | General Site | Central | Bangkok | - | - | 42.3 | 39.2 | 50.2 | 43.9 | Moderate |
| 12 | Roadside Site | Central | Bangkok | 57.3 | 56.8 | 67.2 | 74.5 | - | 64.0 | High |
| 15 | Roadside Site | Central | Bangkok | 24.1 | - | 22.4 | 21.3 | - | 22.6 | Low |
| 16 | Roadside Site | Central | Bangkok | 54.6 | 56.4 | 57.8 | 54.8 | 47.6 | 54.2 | High |
| 19 | General Site | Central | Nonthaburi | 45.2 | 44.8 | 47.6 | 50.3 | 46.3 | 46.8 | Moderate |
| 20 | General Site | Central | Nonthaburi | 29.1 | 29.3 | 41.5 | 40.5 | - | 35.1 | Moderate |
| 22 | General Site | Central | Samut Prakan | 52.7 | 32.8 | 22.1 | - | - | 35.9 | Moderate |
| 23 | General Site | Central | Samut Prakan | - | 45.3 | 48.1 | 54.8 | 47.2 | 48.9 | Moderate |
| 24 | General Site | Central | Samut Prakan | 47.0 | 43.0 | 40.2 | 40.8 | 35.8 | 41.4 | Moderate |
| 25 | General Site | Central | Samut Prakan | 58.7 | 48.8 | 64.2 | 62.1 | 54.9 | 57.7 | High |
| 26 | General Site | Central | Samut Prakan | 44.1 | 39.8 | 42.8 | 45.3 | 39.5 | 42.3 | Moderate |
| 27 | General Site | Central | Samut Sakhon | 25.6 | - | 53.7 | 57.4 | 45.2 | 45.5 | Moderate |
| 28 | General Site | Central | Samut Sakhon | - | - | 88.5 | 51.8 | 44.3 | 61.6 | High |
| 48 | General Site | Central | Ratchaburi | 41.1 | 31.3 | 24.5 | - | - | 32.3 | Moderate |
| 49 | General Site | Central | Saraburi | 94.7 | 107.0 | 98.6 | 95.4 | 97.3 | 98.6 | High |
| 50 | General Site | Central | Saraburi | 38.9 | 24.2 | 21.2 | 18.4 | 34.1 | 27.4 | Low |
| 51 | General Site | Central | Phra Nakhon Si Ayutthaya | 40.0 | - | 55.7 | 55.1 | 49.1 | 50.0 | Moderate |

**Table S13:** Monthly contribution concentrations at monitoring sites across central Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Site 2 | Central (Bangkok) | General site | 2014 | Very Low | <5th Percentile | < 20 | 1 | - | - | - | 5 | 5 | 7 | 12 | 24 | 20 | 13 | 9 | 6 |
| | | | | Low | <25th Percentile | < 31 | 10 | - | - | 1 | 6 | 7 | 10 | 13 | 22 | 19 | 11 | 6 | 5 |
| | | | | Moderate | 25th-75th Percentile | 31-62 | 36 | 1 | 11 | 13 | 10 | 7 | 8 | 6 | 7 | 8 | 8 | 10 | 10 |
| | | | | High | >75th Percentile | > 62 | 40 | 73 | 5 | 2 | 4 | 0.3 | 1 | 0.3 | 0.3 | 0.1 | 4 | 5 | 5 |
| | | | | Very High | >95th Percentile | > 109 | 13 | 93 | 3 | - | 2 | - | - | - | - | - | 1 | 1 | 1 |
| Site 6 | Central (Bangkok) | General site | 2012 | Very Low | <5th Percentile | < 5 | 0.5 | 6 | 3 | 8 | 11 | 16 | 14 | 13 | 5 | 9 | 9 | 5 | 1 |
| | | | | Low | <25th Percentile | < 14 | 6 | 5 | 4 | 6 | 8 | 12 | 9 | 12 | 13 | 14 | 7 | 6 | 2 |
| | | | | Moderate | 25th-75th Percentile | 14-34 | 39 | 8 | 8 | 6 | 8 | 9 | 10 | 9 | 9 | 8 | 9 | 9 | 7 |
| | | | | High | >75th Percentile | > 34 | 42 | 14 | 16 | 17 | 10 | 4 | 5 | 1 | 1 | 2 | 8 | 10 | 12 |
| | | | | Very High | >95th Percentile | > 56 | 12 | 15 | 19 | 19 | 11 | 3 | 5 | 0.4 | 1 | 1 | 7 | 10 | 10 |
| | | | 2014 | Very Low | <5th Percentile | < 16 | 1 | - | - | 0.4 | 1 | 11 | 29 | 11 | 29 | 10 | 8 | 1 | 0.3 |
| | | | | Low | <25th Percentile | < 26 | 8 | - | 0.1 | 1 | 3 | 13 | 21 | 13 | 24 | 12 | 9 | 3 | 1 |
| | | | | Moderate | 25th-75th Percentile | 26-57 | 36 | 3 | 8 | 15 | 9 | 8 | 7 | 9 | 8 | 6 | 9 | 9 | 9 |
| | | | | High | >75th Percentile | > 57 | 41 | 66 | 6 | 2 | 3 | 0.5 | 1 | 0.2 | 0.5 | 0.1 | 4 | 7 | 10 |
| | | | | Very High | >95th Percentile | > 108 | 13 | 85 | 3 | 0.3 | 1 | - | - | 0.1 | - | - | 1 | 3 | 6 |
| | | | 2015 | Very Low | <5th Percentile | < 12 | 1 | - | - | - | - | 5 | 8 | 15 | 17 | 46 | 5 | 2 | 2 |
| | | | | Low | <25th Percentile | < 22 | 8 | - | 0.2 | 0.1 | 1 | 10 | 13 | 12 | 20 | 31 | 7 | 4 | 1 |
| | | | | Moderate | 25th-75th Percentile | 22-50 | 37 | 4 | 7 | 13 | 11 | 10 | 7 | 9 | 6 | 5 | 9 | 10 | 8 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | | High | >75th Percentile | > 50 | 41 | 48 | 22 | 5 | 5 | | 0.2 | 1 | 0.1 | 1 | 1 | 4 | 14 |
| | | | | Very High | >95th Percentile | > 90 | 13 | 60 | 26 | 2 | 1 | - | - | - | - | - | 0.1 | 1 | 11 |
| Site 7 | Central (Bangkok) | General site | 2012 | Very Low | <5th Percentile | < 17 | 1 | 4 | 1 | 0.2 | 6 | 2 | 7 | 10 | 26 | 38 | 2 | 1 | 1 |
| | | | | Low | <25th Percentile | < 27 | 9 | 4 | 2 | 1 | 7 | 4 | 8 | 12 | 23 | 31 | 4 | 3 | 1 |
| | | | | Moderate | 25th-75th Percentile | 27-55 | 40 | 7 | 8 | 7 | 7 | 12 | 11 | 9 | 7 | 5 | 11 | 10 | 5 |
| | | | | High | >75th Percentile | > 55 | 39 | 6 | 8 | 26 | 24 | 1 | 1 | 2 | 0.2 | 1 | 5 | 7 | 20 |
| | | | | Very High | >95th Percentile | > 91 | 11 | 1 | 4 | 33 | 33 | - | 1 | 1 | - | - | 3 | 4 | 20 |
| Site 8 | Central (Bangkok) | General site | 2014 | Very Low | <5th Percentile | < 14 | 1 | 2 | - | 0.1 | 1 | 10 | 7 | 22 | 13 | 36 | 8 | 1 | 0.1 |
| | | | | Low | <25th Percentile | < 27 | 8 | 1 | 0.3 | 1 | 4 | 12 | 10 | 19 | 14 | 26 | 8 | 2 | 1 |
| | | | | Moderate | 25th-75th Percentile | 27-59 | 36 | 2 | 10 | 14 | 9 | 8 | 8 | 8 | 8 | 7 | 9 | 11 | 9 |
| | | | | High | >75th Percentile | > 59 | 41 | 72 | 6 | 1 | 4 | 1 | 1 | 0.4 | 1 | 0.2 | 3 | 3 | 7 |
| | | | | Very High | >95th Percentile | > 109 | 13 | 92 | 3 | 0.1 | 1 | 0.3 | - | - | 0.1 | - | 0.3 | 1 | 2 |
| Site 9 | Central (Bangkok) | General site | 2013 | Very Low | <5th Percentile | < 5 | 1 | 0.2 | 1 | 1 | 17 | 36 | 10 | 19 | 4 | 9 | 2 | 1 | - |
| | | | | Low | <25th Percentile | < 11 | 6 | 2 | 3 | 8 | 11 | 14 | 12 | 12 | 12 | 15 | 6 | 5 | 1 |
| | | | | Moderate | 25th-75th Percentile | 11-26 | 38 | 5 | 6 | 10 | 8 | 7 | 9 | 9 | 10 | 9 | 9 | 11 | 4 |
| | | | | High | >75th Percentile | > 26 | 43 | 27 | 26 | 7 | 2 | 1 | 1 | 2 | 2 | 1 | 9 | 3 | 20 |
| | | | | Very High | >95th Percentile | > 44 | 13 | 31 | 30 | 7 | 1 | 0.3 | 0.2 | 2 | 1 | 0.1 | 8 | 1 | 17 |
| Site 12 | Central (Bangkok) | Roadside site | 2011 | Very Low | <5th Percentile | < 24 | 1 | - | 0.1 | 1 | 1 | 10 | 13 | 35 | 23 | 12 | 5 | 0.1 | 0.2 |
| | | | | Low | <25th Percentile | < 39 | 11 | 0.1 | 0.5 | 2 | 4 | 11 | 13 | 26 | 19 | 14 | 6 | 2 | 2 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | | Moderate | 25th-75th Percentile | 39-72 | 41 | 8 | 11 | 8 | 9 | 8 | 9 | 7 | 6 | 7 | 10 | 11 | 6 |
| | | | | High | >75th Percentile | > 72 | 36 | 32 | 8 | 21 | 11 | 2 | 1 | 1 | 0.4 | 1 | 2 | 3 | 18 |
| | | | | Very High | >95th Percentile | > 106 | 10 | 38 | 7 | 23 | 13 | 1 | 0.1 | 0.2 | - | 0.1 | 0.4 | 1 | 16 |
| | | | 2013 | Very Low | <5th Percentile | < 28 | 1 | - | - | - | 15 | 31 | 18 | 11 | 5 | 10 | 4 | 6 | - |
| | | | | Low | <25th Percentile | < 43 | 11 | 2 | 0.1 | 2 | 13 | 26 | 17 | 14 | 9 | 8 | 3 | 5 | 0.3 |
| | | | | Moderate | 25th-75th Percentile | 43-84 | 40 | 10 | 9 | 14 | 7 | 6 | 7 | 8 | 9 | 9 | 7 | 10 | 5 |
| | | | | High | >75th Percentile | > 84 | 38 | 12 | 20 | 4 | 2 | 0.1 | 0.2 | 0.2 | 0.2 | 2 | 19 | 6 | 34 |
| | | | | Very High | >95th Percentile | > 134 | 11 | 12 | 22 | 3 | 1 | - | - | - | - | 1 | 21 | 3 | 38 |
| Site 14 | Central (Bangkok) | Roadside site | 2015 | Very Low | <5th Percentile | < 8 | 1 | - | 2 | 1 | 2 | 26 | 31 | 11 | 10 | 9 | 8 | 1 | 0.2 |
| | | | | Low | <25th Percentile | < 12 | 9 | 0.1 | 2 | 2 | 3 | 23 | 25 | 12 | 13 | 11 | 6 | 1 | 1 |
| | | | | Moderate | 25th-75th Percentile | 12-23 | 41 | 5 | 7 | 12 | 10 | 7 | 8 | 9 | 8 | 9 | 9 | 9 | 8 |
| | | | | High | >75th Percentile | > 23 | 38 | 38 | 16 | 3 | 3 | 1 | 0.4 | 2 | 0.1 | 2 | 7 | 9 | 19 |
| | | | | Very High | >95th Percentile | > 36 | 11 | 44 | 17 | 2 | 1 | 0.1 | 0.1 | 1 | - | 1 | 6 | 8 | 20 |
| Site 15 | Central (Bangkok) | Roadside site | 2014 | Very Low | <5th Percentile | < 3 | 0.4 | 0.4 | 10 | 9 | 22 | 30 | 5 | 6 | 7 | 2 | 2 | 5 | 0.3 |
| | | | | Low | <25th Percentile | < 10 | 5 | 1 | 6 | 7 | 11 | 13 | 10 | 12 | 11 | 13 | 7 | 7 | 2 |
| | | | | Moderate | 25th-75th Percentile | 10-28 | 36 | 7 | 8 | 8 | 6 | 6 | 8 | 9 | 8 | 9 | 11 | 8 | 10 |
| | | | | High | >75th Percentile | > 28 | 44 | 33 | 8 | 12 | 13 | 19 | 2 | 2 | 3 | 0.5 | 2 | 4 | 3 |
| | | | | Very High | >95th Percentile | > 51 | 14 | 37 | 7 | 13 | 13 | 23 | 1 | 1 | 3 | 0.4 | 0.3 | 2 | 2 |
| Site 16 | | Roadside site | 2013 | Very Low | <5th Percentile | < 13 | 1 | 0.5 | 1 | 4 | 8 | 12 | 12 | 23 | 15 | 17 | 4 | 1 | 3 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | Central (Bangkok) | | | Low | <25th Percentile | < 31 | 7 | 2 | 3 | 7 | 10 | 13 | 11 | 17 | 15 | 13 | 3 | 3 | 2 |
| | | | | Moderate | 25th-75th Percentile | 31-78 | 39 | 8 | 6 | 10 | 9 | 8 | 9 | 8 | 8 | 8 | 9 | 11 | 6 |
| | | | | High | >75th Percentile | > 78 | 41 | 22 | 23 | 5 | 4 | 1 | 2 | 1 | 1 | 2 | 10 | 4 | 25 |
| | | | | Very High | >95th Percentile | > 130 | 12 | 25 | 31 | 5 | 4 | 0.2 | 1 | 0.2 | 0.4 | 1 | 7 | 1 | 26 |
| | | | 2015 | Very Low | <5th Percentile | < 8 | 0.4 | 1 | 7 | 10 | 5 | 13 | 23 | 9 | 10 | 19 | 5 | 0.3 | 1 |
| | | | | Low | <25th Percentile | < 23 | 6 | 1 | 6 | 15 | 7 | 13 | 15 | 9 | 13 | 12 | 5 | 1 | 1 |
| | | | | Moderate | 25th-75th Percentile | 23-65 | 38 | 9 | 7 | 7 | 10 | 9 | 8 | 8 | 9 | 9 | 9 | 8 | 8 |
| | | | | High | >75th Percentile | > 65 | 43 | 22 | 14 | 3 | 3 | 1 | 1 | 1 | 0.5 | 3 | 15 | 14 | 21 |
| | | | | Very High | >95th Percentile | > 110 | 12 | 27 | 16 | 2 | 1 | 1 | - | 0.1 | - | 1 | 16 | 13 | 23 |
| Site 17 | Central (Bangkok) | General site | 2015 | Very Low | <5th Percentile | < 13 | 1 | - | - | 0.1 | 0.4 | 12 | 6 | 30 | 22 | 24 | 4 | 1 | 0.1 |
| | | | | Low | <25th Percentile | < 24 | 9 | - | 0.3 | 1 | 2 | 16 | 10 | 23 | 20 | 19 | 5 | 2 | 1 |
| | | | | Moderate | 25th-75th Percentile | 24-50 | 37 | 3 | 7 | 14 | 10 | 7 | 9 | 8 | 6 | 7 | 11 | 10 | 8 |
| | | | | High | >75th Percentile | > 50 | 41 | 43 | 25 | 3 | 4 | 0.1 | 0.1 | 1 | 0.4 | 1 | 3 | 6 | 13 |
| | | | | Very High | >95th Percentile | > 91 | 12 | 53 | 30 | 1 | 2 | - | 0.1 | - | 0.2 | 0.1 | 1 | 3 | 10 |
| Site 18 | Central (Bangkok) | General site | 2013 | Very Low | <5th Percentile | < 10 | 1 | 0.2 | - | 2 | 11 | 12 | 7 | 29 | 18 | 15 | 6 | 1 | - |
| | | | | Low | <25th Percentile | < 23 | 8 | 2 | 1 | 6 | 12 | 15 | 11 | 17 | 16 | 13 | 5 | 3 | 1 |
| | | | | Moderate | 25th-75th Percentile | 23-56 | 38 | 8 | 8 | 11 | 8 | 8 | 10 | 8 | 9 | 6 | 8 | 11 | 5 |
| | | | | High | >75th Percentile | > 56 | 42 | 25 | 24 | 4 | 3 | 1 | 0.5 | 2 | 0.4 | 1 | 10 | 3 | 27 |
| | | | | Very High | >95th Percentile | > 95 | 13 | 29 | 29 | 3 | 2 | - | - | - | - | - | 8 | 1 | 27 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | 2014 | Very Low | <5th Percentile | < 8 | 0.5 | - | 2 | 3 | 8 | 21 | 18 | 14 | 15 | 12 | 3 | 1 | 2 |
| | | | | Low | <25th Percentile | < 20 | 6 | 0.1 | 2 | 4 | 9 | 17 | 14 | 15 | 16 | 13 | 5 | 2 | 2 |
| | | | | Moderate | 25th-75th Percentile | 20-51 | 37 | 3 | 11 | 11 | 9 | 8 | 8 | 8 | 8 | 7 | 10 | 9 | 8 |
| | | | | High | >75th Percentile | > 51 | 42 | 63 | 3 | 1 | 3 | 1 | 1 | 0.4 | 1 | 0.2 | 7 | 6 | 14 |
| | | | | Very High | >95th Percentile | > 92 | 14 | 80 | 1 | 0.2 | 1 | 0.1 | - | - | - | - | 4 | 2 | 10 |
| Site 19 | Central | General site | 2012 | Very Low | <5th Percentile | < 11 | 1 | 2 | 2 | 3 | 10 | 12 | 5 | 14 | 14 | 27 | 7 | 3 | - |
| | | | | Low | <25th Percentile | < 25 | 8 | 3 | 4 | 5 | 11 | 11 | 6 | 14 | 13 | 21 | 7 | 4 | 0.1 |
| | | | | Moderate | 25th-75th Percentile | 25-58 | 37 | 8 | 7 | 7 | 8 | 11 | 12 | 9 | 8 | 7 | 9 | 9 | 6 |
| | | | | High | >75th Percentile | > 58 | 42 | 24 | 16 | 13 | 8 | 1 | 1 | 1 | 0.3 | 1 | 7 | 11 | 17 |
| | | | | Very High | >95th Percentile | > 101 | 12 | 30 | 17 | 11 | 9 | - | 0.2 | - | 0.1 | - | 6 | 10 | 18 |
| Site 20 | Central | General site | 2011 | Very Low | <5th Percentile | < 5 | 0.4 | 4 | 3 | 4 | 6 | 10 | 10 | 17 | 17 | 16 | 9 | 3 | 1 |
| | | | | Low | <25th Percentile | < 16 | 7 | 4 | 3 | 5 | 6 | 9 | 11 | 16 | 15 | 14 | 11 | 4 | 2 |
| | | | | Moderate | 25th-75th Percentile | 16-39 | 39 | 6 | 8 | 8 | 8 | 9 | 8 | 8 | 8 | 8 | 10 | 11 | 8 |
| | | | | High | >75th Percentile | > 39 | 42 | 21 | 15 | 14 | 11 | 10 | 4 | 2 | 1 | 1 | 2 | 9 | 8 |
| | | | | Very High | >95th Percentile | > 63 | 12 | 22 | 18 | 15 | 11 | 12 | 4 | 2 | 1 | 0.3 | 1 | 10 | 4 |
| Site 21 | Central | General site | 2013 | Very Low | <5th Percentile | < 9 | 0.4 | 0.2 | 1 | 3 | 4 | 14 | 13 | 19 | 16 | 20 | 6 | 4 | 0.5 |
| | | | | Low | <25th Percentile | < 26 | 7 | 1 | 1 | 4 | 7 | 14 | 12 | 17 | 14 | 16 | 6 | 6 | 1 |
| | | | | Moderate | 25th-75th Percentile | 26-69 | 38 | 6 | 5 | 11 | 9 | 8 | 8 | 8 | 9 | 7 | 9 | 12 | 7 |
| | | | | High | >75th Percentile | > 69 | 43 | 32 | 29 | 9 | 7 | 1 | 1 | 0.4 | 1 | 1 | 4 | 1 | 13 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | | Very High | >95th Percentile | > 118 | 12 | 38 | 37 | 8 | 6 | - | - | - | 0.1 | 0.1 | 1 | 0.4 | 9 |
| | | | 2014 | Very Low | <5th Percentile | < 8 | 0.4 | - | - | - | 5 | 13 | 10 | 20 | 15 | 16 | 13 | 4 | 3 |
| | | | | Low | <25th Percentile | < 23 | 6 | 0.2 | 1 | 1 | 5 | 13 | 13 | 17 | 14 | 16 | 10 | 6 | 3 |
| | | | | Moderate | 25th-75th Percentile | 23-65 | 37 | 4 | 9 | 8 | 8 | 9 | 9 | 7 | 9 | 7 | 9 | 11 | 10 |
| | | | | High | >75th Percentile | > 65 | 44 | 39 | 9 | 22 | 12 | 1 | 1 | 0.4 | 1 | 1 | 2 | 3 | 9 |
| | | | | Very High | >95th Percentile | > 115 | 13 | 46 | 7 | 24 | 12 | 0.5 | 0.2 | 0.2 | 1 | 0.5 | 0.1 | 1 | 7 |
| Site 22 | Central | General site | 2012 | Very Low | <5th Percentile | < 10 | 1 | 1 | 0.4 | 0.5 | 21 | 17 | 36 | 17 | 3 | 3 | 0.3 | 0.1 | - |
| | | | | Low | <25th Percentile | < 18 | 8 | 2 | 2 | 5 | 19 | 18 | 27 | 16 | 5 | 4 | 1 | 1 | - |
| | | | | Moderate | 25th-75th Percentile | 18-42 | 38 | 9 | 8 | 8 | 7 | 5 | 7 | 10 | 11 | 11 | 9 | 8 | 6 |
| | | | | High | >75th Percentile | > 42 | 41 | 7 | 6 | 5 | 1 | - | 0.3 | 1 | 2 | 3 | 22 | 20 | 33 |
| | | | | Very High | >95th Percentile | > 75 | 12 | 4 | 5 | 2 | 0.1 | - | - | - | 1 | 2 | 26 | 22 | 39 |
| Site 23 | Central | General site | 2013 | Very Low | <5th Percentile | < 14 | 1 | - | - | 1 | 10 | 26 | 12 | 20 | 25 | 4 | 2 | 0.3 | - |
| | | | | Low | <25th Percentile | < 25 | 8 | 0.4 | 0.1 | 4 | 10 | 22 | 12 | 19 | 18 | 9 | 3 | 2 | - |
| | | | | Moderate | 25th-75th Percentile | 25-58 | 34 | 7 | 8 | 12 | 8 | 7 | 11 | 8 | 8 | 9 | 9 | 11 | 2 |
| | | | | High | >75th Percentile | > 58 | 44 | 22 | 19 | 4 | 1 | 0.3 | 1 | 0.3 | 0.3 | 1 | 4 | 4 | 44 |
| | | | | Very High | >95th Percentile | > 125 | 14 | 24 | 19 | 2 | - | - | - | - | 0.1 | - | 1 | 1 | 53 |
| | | | 2014 | Very Low | <5th Percentile | < 20 | 1 | 0.2 | 0.1 | 4 | 6 | 28 | 28 | 6 | 6 | 16 | 4 | 1 | - |
| | | | | Low | <25th Percentile | < 32 | 9 | 0.1 | 1 | 4 | 10 | 23 | 22 | 9 | 9 | 15 | 4 | 2 | 0.4 |
| | | | | Moderate | 25th-75th Percentile | 32-66 | 36 | 2 | 12 | 11 | 7 | 5 | 8 | 10 | 10 | 9 | 10 | 9 | 8 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | | High | >75th Percentile | > 66 | 40 | 64 | 2 | 1 | 2 | 1 | 1 | 0.4 | 1 | 0.4 | 7 | 8 | 13 |
| | | | | Very High | >95th Percentile | > 124 | 13 | 83 | 1 | - | - | 1 | - | - | - | - | 3 | 3 | 8 |
| Site 24 | Central | General site | 2012 | Very Low | <5th Percentile | < 10 | 1 | 12 | 11 | 11 | 20 | 13 | 6 | 5 | 7 | 9 | 2 | 2 | 1 |
| | | | | Low | <25th Percentile | < 23 | 7 | 7 | 6 | 7 | 13 | 12 | 7 | 11 | 13 | 14 | 4 | 4 | 2 |
| | | | | Moderate | 25th-75th Percentile | 23-56 | 38 | 8 | 7 | 7 | 7 | 9 | 11 | 9 | 8 | 8 | 10 | 8 | 8 |
| | | | | High | >75th Percentile | > 56 | 42 | 13 | 16 | 20 | 13 | 2 | 1 | 1 | 0.2 | 1 | 11 | 9 | 12 |
| | | | | Very High | >95th Percentile | > 99 | 13 | 13 | 19 | 23 | 15 | 1 | 0.2 | 1 | - | 0.1 | 11 | 8 | 9 |
| | | | 2013 | Very Low | <5th Percentile | < 11 | 1 | 1 | 1 | 0.3 | 15 | 11 | 9 | 15 | 12 | 21 | 9 | 5 | 1 |
| | | | | Low | <25th Percentile | < 22 | 8 | 1 | 1 | 3 | 13 | 14 | 10 | 15 | 12 | 17 | 7 | 5 | 1 |
| | | | | Moderate | 25th-75th Percentile | 22-51 | 36 | 6 | 8 | 12 | 8 | 8 | 10 | 9 | 9 | 8 | 8 | 12 | 4 |
| | | | | High | >75th Percentile | > 51 | 42 | 31 | 17 | 4 | 3 | 1 | 1 | 0.2 | 1 | 1 | 11 | 3 | 30 |
| | | | | Very High | >95th Percentile | > 96 | 13 | 39 | 18 | 2 | 1 | - | - | - | - | 0.1 | 8 | 1 | 30 |
| | | | 2014 | Very Low | <5th Percentile | < 12 | 1 | - | - | 3 | 14 | 14 | 13 | 18 | 18 | 11 | 7 | 1 | 1 |
| | | | | Low | <25th Percentile | < 23 | 8 | 0.1 | 0.4 | 4 | 13 | 14 | 12 | 16 | 17 | 13 | 7 | 2 | 2 |
| | | | | Moderate | 25th-75th Percentile | 23-49 | 36 | 3 | 12 | 12 | 7 | 8 | 8 | 8 | 8 | 8 | 8 | 9 | 8 |
| | | | | High | >75th Percentile | > 49 | 42 | 65 | 3 | 1 | 3 | 1 | 1 | 1 | 1 | 0.5 | 6 | 7 | 11 |
| | | | | Very High | >95th Percentile | > 94 | 14 | 82 | 1 | - | 2 | 1 | 0.1 | 0.1 | - | 0.2 | 3 | 4 | 7 |
| | | | 2015 | Very Low | <5th Percentile | < 10 | 1 | - | 0.4 | 1 | 0.4 | 18 | 23 | 8 | 17 | 23 | 9 | 0.5 | 1 |
| | | | | Low | <25th Percentile | < 20 | 7 | 0.1 | 1 | 2 | 2 | 18 | 20 | 10 | 17 | 19 | 8 | 2 | 1 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 20-45 | 38 | 5 | 7 | 12 | 10 | 8 | 7 | 9 | 7 | 7 | 9 | 10 | 8 |
| | | | | High | $>75^{th}$ Percentile | > 45 | 42 | 36 | 26 | 2 | 4 | 0.3 | 0.1 | 1 | 0.1 | 2 | 4 | 5 | 19 |
| | | | | Very High | $>95^{th}$ Percentile | > 79 | 12 | 40 | 31 | 1 | 2 | - | - | 0.1 | - | 2 | 3 | 3 | 19 |
| Site 25 | Central | General site | 2012 | Very Low | $<5^{th}$ Percentile | < 15 | 1 | 15 | 0.3 | 2 | 13 | 16 | 8 | 20 | 5 | 19 | 2 | 0.3 | - |
| | | | | Low | $<25^{th}$ Percentile | < 27 | 8 | 10 | 1 | 4 | 10 | 15 | 14 | 18 | 8 | 15 | 4 | 1 | 0.2 |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 27-63 | 37 | 7 | 8 | 8 | 8 | 9 | 7 | 8 | 11 | 9 | 11 | 8 | 8 |
| | | | | High | $>75^{th}$ Percentile | > 63 | 42 | 7 | 7 | 13 | 13 | 1 | 0.2 | 0.3 | 1 | 2 | 6 | 22 | 29 |
| | | | | Very High | $>95^{th}$ Percentile | > 110 | 12 | 4 | 5 | 11 | 14 | 0.1 | - | - | - | - | 4 | 25 | 36 |
| | | | 2013 | Very Low | $<5^{th}$ Percentile | < 22 | 1 | - | - | 1 | 15 | 54 | 12 | 1 | 2 | 9 | 5 | 2 | - |
| | | | | Low | $<25^{th}$ Percentile | < 39 | 9 | 1 | 0.3 | 3 | 16 | 39 | 11 | 6 | 5 | 11 | 4 | 3 | 0.1 |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 39-81 | 38 | 8 | 8 | 12 | 7 | 3 | 9 | 10 | 11 | 9 | 8 | 11 | 4 |
| | | | | High | $>75^{th}$ Percentile | > 81 | 39 | 11 | 24 | 4 | 1 | 0.4 | 1 | 1 | 2 | 2 | 12 | 6 | 35 |
| | | | | Very High | $>95^{th}$ Percentile | > 137 | 12 | 9 | 29 | 4 | 0.2 | 0.1 | - | 1 | 1 | 1 | 11 | 5 | 40 |
| Site 26 | Central | General site | 2013 | Very Low | $<5^{th}$ Percentile | < 8 | 0.4 | - | 0.4 | 2 | 9 | 14 | 12 | 14 | 14 | 22 | 8 | 4 | 1 |
| | | | | Low | $<25^{th}$ Percentile | < 20 | 6 | 1 | 2 | 5 | 8 | 16 | 13 | 13 | 14 | 17 | 6 | 5 | 1 |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 20-56 | 34 | 8 | 7 | 9 | 9 | 8 | 9 | 9 | 9 | 8 | 9 | 11 | 4 |
| | | | | High | $>75^{th}$ Percentile | > 56 | 45 | 19 | 19 | 5 | 2 | 1 | 1 | 1 | 0.2 | 1 | 13 | 5 | 35 |
| | | | | Very High | $>95^{th}$ Percentile | > 110 | 14 | 20 | 21 | 5 | 0.5 | 0.2 | - | 0.1 | - | - | 12 | 3 | 38 |
| | | | 2014 | Very Low | $<5^{th}$ Percentile | < 9 | 0.5 | 0.3 | 4 | 1 | 8 | 20 | 23 | 17 | 7 | 12 | 2 | 1 | 4 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | | Low | <25th Percentile | < 23 | 6 | 1 | 4 | 3 | 9 | 17 | 17 | 16 | 12 | 13 | 5 | 2 | 3 |
| | | | | Moderate | 25th-75th Percentile | 23-57 | 35 | 4 | 10 | 13 | 8 | 8 | 7 | 8 | 8 | 8 | 9 | 10 | 8 |
| | | | | High | >75th Percentile | > 57 | 44 | 55 | 5 | 2 | 4 | 1 | 1 | 1 | 1 | 1 | 8 | 10 | 11 |
| | | | | Very High | >95th Percentile | > 109 | 14 | 70 | 4 | 1 | 1 | - | 0.2 | 1 | 0.1 | - | 7 | 9 | 8 |
| Site 27 | Central | | 2014 | Very Low | <5th Percentile | < 13 | 0.5 | - | 1 | - | - | 2 | 1 | 2 | 34 | 38 | 22 | - | - |
| | | | | Low | <25th Percentile | < 33 | 8 | - | 2 | 4 | 4 | 6 | 7 | 9 | 22 | 27 | 16 | 3 | 1 |
| | | | | Moderate | 25th-75th Percentile | 33-73 | 39 | 2 | 12 | 13 | 11 | 9 | 8 | 10 | 6 | 5 | 7 | 10 | 6 |
| | | | | High | >75th Percentile | > 73 | 41 | 58 | 4 | 1 | 4 | 1 | 2 | 2 | 1 | 0.3 | 4 | 9 | 15 |
| | | | | Very High | >95th Percentile | > 127 | 13 | 75 | 3 | - | 2 | - | 0.3 | 0.3 | 0.1 | - | 2 | 8 | 10 |
| Site 28 | Central | General site | 2014 | Very Low | <5th Percentile | < 9 | 0.4 | - | - | 1 | 5 | 12 | 30 | 13 | 15 | 16 | 5 | 3 | - |
| | | | | Low | <25th Percentile | < 21 | 5 | - | 0.3 | 2 | 10 | 17 | 19 | 13 | 15 | 15 | 4 | 2 | 0.2 |
| | | | | Moderate | 25th-75th Percentile | 21-66 | 31 | 3 | 12 | 12 | 8 | 7 | 8 | 9 | 8 | 8 | 10 | 9 | 6 |
| | | | | High | >75th Percentile | > 66 | 47 | 52 | 2 | 0.2 | 1 | 1 | 1 | 1 | 1 | 0.4 | 9 | 10 | 22 |
| | | | | Very High | >95th Percentile | > 146 | 16 | 67 | 2 | - | - | 0.1 | - | 0.3 | - | - | 7 | 6 | 18 |
| Site 47 | Central | General site | 2015 | Very Low | <5th Percentile | < 8 | 0.4 | - | - | - | - | 4 | 13 | 10 | 42 | 18 | 3 | - | 10 |
| | | | | Low | <25th Percentile | < 19 | 6 | 0.1 | - | - | 1 | 10 | 19 | 10 | 31 | 20 | 7 | - | 4 |
| | | | | Moderate | 25th-75th Percentile | 19-57 | 37 | 3 | 7 | 14 | 13 | 11 | 6 | 11 | 4 | 5 | 7 | 10 | 7 |
| | | | | High | >75th Percentile | > 57 | 44 | 30 | 37 | 4 | 4 | 0.1 | - | 0.2 | 0.2 | 0.4 | 4 | 6 | 14 |
| | | | | Very High | >95th Percentile | > 105 | 13 | 34 | 51 | 1 | 2 | - | - | - | 0.3 | - | 1 | 1 | 9 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Site 49 | Central | General site | 2011 | Very Low | <5th Percentile | < 21 | 1 | - | 1 | 8 | 1 | 7 | 13 | 16 | 12 | 27 | 13 | 0.2 | 1 |
| | | | | Low | <25th Percentile | < 47 | 7 | 0.4 | 3 | 5 | 4 | 11 | 14 | 17 | 12 | 22 | 9 | 2 | 2 |
| | | | | Moderate | 25th-75th Percentile | 47-124 | 37 | 10 | 7 | 7 | 9 | 8 | 8 | 6 | 6 | 6 | 11 | 10 | 12 |
| | | | | High | >75th Percentile | > 124 | 42 | 18 | 26 | 13 | 12 | 4 | 1 | 1 | 2 | 2 | 6 | 11 | 5 |
| | | | | Very High | >95th Percentile | > 218 | 13 | 20 | 33 | 13 | 12 | 1 | 1 | 0.3 | 2 | 1 | 4 | 11 | 2 |
| | | | 2012 | Very Low | <5th Percentile | < 22 | 1 | 2 | 1 | 1 | 10 | 9 | 6 | 31 | 25 | 13 | 1 | 2 | - |
| | | | | Low | <25th Percentile | < 48 | 6 | 4 | 3 | 4 | 8 | 11 | 11 | 23 | 20 | 10 | 1 | 2 | 1 |
| | | | | Moderate | 25th-75th Percentile | 48-145 | 36 | 11 | 8 | 10 | 8 | 8 | 8 | 6 | 7 | 8 | 9 | 8 | 8 |
| | | | | High | >75th Percentile | > 145 | 45 | 9 | 14 | 9 | 4 | 1 | 1 | 1 | 1 | 6 | 14 | 14 | 26 |
| | | | | Very High | >95th Percentile | > 268 | 13 | 11 | 17 | 8 | 4 | 0.1 | - | 0.1 | 0.1 | 3 | 10 | 13 | 34 |
| | | | 2014 | Very Low | <5th Percentile | < 19 | 1 | - | 1 | 0.2 | 4 | 6 | 13 | 25 | 34 | 12 | 1 | 1 | 1 |
| | | | | Low | <25th Percentile | < 44 | 6 | 0.3 | 1 | 2 | 7 | 12 | 15 | 22 | 24 | 12 | 2 | 1 | 2 |
| | | | | Moderate | 25th-75th Percentile | 44-124 | 36 | 8 | 10 | 11 | 10 | 8 | 8 | 6 | 5 | 7 | 9 | 8 | 11 |
| | | | | High | >75th Percentile | > 124 | 43 | 36 | 9 | 4 | 3 | 3 | 1 | 0.3 | 1 | 7 | 14 | 15 | 7 |
| | | | | Very High | >95th Percentile | > 234 | 14 | 47 | 10 | 2 | 2 | 1 | 0.4 | - | 1 | 7 | 13 | 14 | 3 |
| | | | 2015 | Very Low | <5th Percentile | < 23 | 1 | - | 0.2 | 1 | 2 | 12 | 10 | 22 | 11 | 31 | 10 | 1 | 0.3 |
| | | | | Low | <25th Percentile | < 45 | 7 | 0.5 | 2 | 2 | 3 | 15 | 14 | 20 | 15 | 20 | 6 | 1 | 1 |
| | | | | Moderate | 25th-75th Percentile | 45-124 | 34 | 9 | 9 | 13 | 12 | 8 | 5 | 7 | 6 | 7 | 8 | 8 | 8 |
| | | | | High | >75th Percentile | > 124 | 45 | 26 | 11 | 3 | 5 | 1 | 1 | 1 | 1 | 5 | 12 | 15 | 19 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Monthly Contribution (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| | | | | Very High | >95th Percentile | > 256 | 14 | 34 | 10 | 3 | 3 | 1 | 0.1 | - | 0.4 | 4 | 10 | 15 | 21 |
| Site 51 | Central | | 2014 | Very Low | <5th Percentile | < 14 | 1 | - | - | - | 16 | 20 | 5 | 15 | 19 | 21 | 4 | 1 | - |
| | | | | Low | <25th Percentile | < 28 | 7 | - | - | 0.3 | 11 | 17 | 9 | 16 | 19 | 18 | 7 | 2 | 0.4 |
| | | | | Moderate | 25th-75th Percentile | 28-72 | 37 | 3 | 11 | 13 | 8 | 8 | 8 | 7 | 7 | 7 | 10 | 11 | 7 |
| | | | | High | >75th Percentile | > 72 | 42 | 60 | 6 | 4 | 4 | 0.4 | 0.3 | - | 0.2 | 0.3 | 3 | 3 | 17 |
| | | | | Very High | >95th Percentile | > 131 | 13 | 77 | 3 | 1 | 3 | - | - | - | - | - | 1 | 1 | 14 |

**Table S14:** Country contribution concentrations at monitoring sites across central Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Cambodia | China | India | Indonesia | Laos | Marine | Myanmar | Thailand | Vietnam |
| Site 2 | Central (Bangkok) | General site | 2014 | Very Low | <5th Percentile | < 20 | 1 | 2 | 0.1 | 0.1 | - | 1 | 64 | 4 | 26 | 2 |
| | | | | Low | <25th Percentile | < 31 | 10 | 2 | 0.2 | 0.2 | - | 1 | 66 | 5 | 25 | 1 |
| | | | | Moderate | 25th-75th Percentile | 31-62 | 36 | 1 | 1 | 0.1 | - | 2 | 61 | 3 | 30 | 2 |
| | | | | High | >75th Percentile | > 62 | 40 | 3 | 6 | - | - | 6 | 21 | 1 | 60 | 4 |
| | | | | Very High | >95th Percentile | > 109 | 13 | 3 | 7 | - | - | 5 | 16 | 0.3 | 65 | 3 |
| Site 6 | Central (Bangkok) | General site | 2012 | Very Low | <5th Percentile | < 5 | 0.5 | 2 | - | 0.1 | - | 0.4 | 72 | 4 | 22 | 0.3 |
| | | | | Low | <25th Percentile | < 14 | 6 | 1 | 0.1 | 0.2 | - | 1 | 69 | 4 | 24 | 0.5 |
| | | | | Moderate | 25th-75th Percentile | 14-34 | 39 | 2 | 1 | 0.1 | - | 2 | 60 | 3 | 32 | 1 |
| | | | | High | >75th Percentile | > 34 | 42 | 4 | 1 | 0.1 | - | 3 | 38 | 2 | 50 | 1 |
| | | | | Very High | >95th Percentile | > 56 | 12 | 5 | 1 | 0.1 | - | 3 | 36 | 2 | 52 | 1 |
| | | | 2014 | Very Low | <5th Percentile | < 16 | 1 | 0.2 | 0.3 | 0.3 | - | 1 | 73 | 6 | 19 | 1 |
| | | | | Low | <25th Percentile | < 26 | 8 | 0.3 | 0.4 | 0.2 | - | 1 | 70 | 6 | 22 | 1 |
| | | | | Moderate | 25th-75th Percentile | 26-57 | 36 | 1 | 2 | 0.1 | - | 2 | 61 | 3 | 30 | 2 |
| | | | | High | >75th Percentile | > 57 | 41 | 2 | 5 | - | - | 7 | 18 | 0.5 | 63 | 4 |
| | | | | Very High | >95th Percentile | > 108 | 13 | 3 | 5 | - | - | 7 | 13 | 0.1 | 69 | 3 |
| | | | 2015 | Very Low | <5th Percentile | < 12 | 1 | 0.1 | 0.1 | 0.3 | 0.1 | 1 | 75 | 6 | 17 | 0.2 |
| | | | | Low | <25th Percentile | < 22 | 8 | 0.2 | 0.3 | 0.2 | 0.1 | 1 | 73 | 6 | 19 | 0.3 |
| | | | | Moderate | 25th-75th Percentile | 22-50 | 37 | 2 | 1 | - | - | 3 | 60 | 4 | 28 | 2 |
| | | | | High | >75th Percentile | > 50 | 41 | 4 | 2 | - | - | 7 | 26 | 1 | 55 | 4 |
| | | | | Very High | >95th Percentile | > 90 | 13 | 5 | 2 | - | - | 8 | 22 | 1 | 58 | 4 |
| Site 7 | Central (Bangkok) | General site | 2012 | Very Low | <5th Percentile | < 17 | 1 | 1 | - | 0.2 | - | 0.4 | 75 | 6 | 18 | 0.2 |
| | | | | Low | <25th Percentile | < 27 | 9 | 1 | - | 0.2 | - | 0.3 | 75 | 5 | 19 | 0.2 |
| | | | | Moderate | 25th-75th Percentile | 27-55 | 40 | 2 | 0.2 | 0.1 | - | 2 | 60 | 3 | 32 | 1 |
| | | | | High | >75th Percentile | > 55 | 39 | 3 | 1 | 0.1 | - | 3 | 35 | 3 | 54 | 1 |
| | | | | Very High | >95th Percentile | > 91 | 11 | 3 | 1 | 0.1 | - | 3 | 32 | 4 | 56 | 1 |
| Site 8 | Central (Bangkok) | General site | 2014 | Very Low | <5th Percentile | < 14 | 1 | 0.3 | 0.4 | 0.2 | - | 0.4 | 74 | 6 | 18 | 0.4 |
| | | | | Low | <25th Percentile | < 27 | 8 | 0.2 | 0.3 | 0.2 | - | 1 | 72 | 6 | 21 | 0.5 |
| | | | | Moderate | 25th-75th Percentile | 27-59 | 36 | 0.5 | 1 | 0.1 | - | 2 | 62 | 3 | 30 | 2 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Cambodia | China | India | Indonesia | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | > 59 | 41 | 3 | 5 | - | - | 6 | 36 | 2 | 43 | 6 |
| | | | | Very High | >95th Percentile | > 109 | 13 | 4 | 5 | - | - | 5 | 17 | 0.2 | 66 | 3 |
| Site 9 | Central (Bangkok) | General site | 2013 | Very Low | <5th Percentile | < 5 | 1 | 1 | 0.1 | 0.1 | 0.1 | 0.2 | 78 | 5 | 15 | 0.5 |
| | | | | Low | <25th Percentile | < 11 | 6 | 1 | 1 | 0.1 | 0.1 | 1 | 75 | 5 | 17 | 1 |
| | | | | Moderate | 25th-75th Percentile | 11-26 | 38 | 1 | 1 | 0.1 | 0.1 | 2 | 60 | 4 | 29 | 2 |
| | | | | High | >75th Percentile | > 26 | 43 | 2 | 1 | - | - | 6 | 21 | 2 | 65 | 3 |
| | | | | Very High | >95th Percentile | > 44 | 13 | 2 | 1 | - | - | 6 | 18 | 2 | 69 | 3 |
| Site 12 | Central (Bangkok) | Roadside site | 2011 | Very Low | <5th Percentile | < 24 | 1 | - | 0.4 | 0.3 | - | 1 | 77 | 5 | 17 | 0.2 |
| | | | | Low | <25th Percentile | < 39 | 11 | 0.1 | 1 | 0.2 | - | 1 | 74 | 5 | 18 | 1 |
| | | | | Moderate | 25th-75th Percentile | 39-72 | 41 | 0.2 | 4 | 0.1 | - | 4 | 53 | 4 | 33 | 2 |
| | | | | High | >75th Percentile | > 72 | 36 | 0.5 | 4 | - | - | 8 | 25 | 1 | 57 | 4 |
| | | | | Very High | >95th Percentile | > 106 | 10 | 1 | 3 | - | - | 9 | 22 | 0.2 | 60 | 4 |
| | | | 2013 | Very Low | <5th Percentile | < 28 | 1 | 0.1 | 0.1 | - | - | 3 | 72 | 5 | 19 | 2 |
| | | | | Low | <25th Percentile | < 43 | 11 | 0.2 | 0.4 | 0.1 | 0.1 | 2 | 73 | 5 | 18 | 1 |
| | | | | Moderate | 25th-75th Percentile | 43-84 | 40 | 1 | 2 | 0.1 | 0.1 | 3 | 59 | 4 | 29 | 2 |
| | | | | High | >75th Percentile | > 84 | 38 | 1 | 1 | - | - | 7 | 16 | 1 | 70 | 4 |
| | | | | Very High | >95th Percentile | > 134 | 11 | 1 | 1 | - | - | 7 | 12 | 1 | 76 | 3 |
| Site 14 | Central (Bangkok) | Roadside site | 2015 | Very Low | <5th Percentile | < 8 | 1 | 0.1 | - | 0.1 | - | 0.4 | 75 | 6 | 18 | 0.1 |
| | | | | Low | <25th Percentile | < 12 | 9 | 0.2 | 0.1 | 0.2 | - | 0.4 | 75 | 6 | 18 | 0.1 |
| | | | | Moderate | 25th-75th Percentile | 12-23 | 41 | 1 | 1 | 0.1 | - | 3 | 61 | 4 | 28 | 2 |
| | | | | High | >75th Percentile | > 23 | 38 | 7 | 1 | - | - | 6 | 22 | 1 | 60 | 3 |
| | | | | Very High | >95th Percentile | > 36 | 11 | 8 | 1 | - | - | 7 | 20 | 1 | 62 | 2 |
| Site 15 | Central (Bangkok) | Roadside site | 2014 | Very Low | <5th Percentile | < 3 | 0.4 | 1 | - | 0.1 | - | 0.3 | 75 | 3 | 20 | 1 |
| | | | | Low | <25th Percentile | < 10 | 5 | 1 | 1 | 0.1 | - | 1 | 68 | 4 | 25 | 1 |
| | | | | Moderate | 25th-75th Percentile | 10-28 | 36 | 1 | 2 | 0.1 | - | 3 | 54 | 3 | 34 | 2 |
| | | | | High | >75th Percentile | > 28 | 44 | 3 | 1 | - | - | 3 | 49 | 2 | 41 | 2 |
| | | | | Very High | >95th Percentile | > 51 | 14 | 3 | 0.3 | - | - | 2 | 50 | 2 | 42 | 1 |
| Site 16 | Central (Bangkok) | Roadside site | 2013 | Very Low | <5th Percentile | < 13 | 1 | 1 | 0.1 | 0.1 | 0.1 | 1 | 74 | 5 | 18 | 1 |
| | | | | Low | <25th Percentile | < 31 | 7 | 1 | 0.4 | 0.1 | 0.1 | 1 | 74 | 5 | 18 | 1 |
| | | | | Moderate | 25th-75th Percentile | 31-78 | 39 | 1 | 2 | 0.1 | 0.1 | 3 | 56 | 4 | 32 | 3 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Cambodia | China | India | Indonesia | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | > 78 | 41 | 2 | 1 | - | - | 6 | 22 | 2 | 64 | 3 |
| | | | | Very High | >95th Percentile | > 130 | 12 | 2 | 1 | - | - | 6 | 18 | 1 | 69 | 3 |
| | | | 2015 | Very Low | <5th Percentile | < 8 | 0.4 | - | - | 0.2 | 0.1 | 0.1 | 80 | 5 | 14 | 0.1 |
| | | | | Low | <25th Percentile | < 23 | 6 | 0.4 | 0.1 | 0.1 | - | 0.4 | 78 | 5 | 16 | 0.3 |
| | | | | Moderate | 25th-75th Percentile | 23-65 | 38 | 1 | 2 | 0.1 | - | 3 | 57 | 4 | 31 | 2 |
| | | | | High | >75th Percentile | > 65 | 43 | 4 | 1 | - | - | 6 | 26 | 2 | 57 | 3 |
| | | | | Very High | >95th Percentile | > 110 | 12 | 4 | 1 | - | - | 6 | 23 | 2 | 61 | 3 |
| Site 17 | Central (Bangkok) | General site | 2015 | Very Low | <5th Percentile | < 13 | 1 | - | - | 0.2 | - | 0.3 | 79 | 5 | 16 | 0.1 |
| | | | | Low | <25th Percentile | < 24 | 9 | 0.2 | 0.1 | 0.2 | - | 1 | 76 | 5 | 17 | 0.2 |
| | | | | Moderate | 25th-75th Percentile | 24-50 | 37 | 2 | 1 | 0.1 | - | 3 | 60 | 4 | 29 | 1 |
| | | | | High | >75th Percentile | > 50 | 41 | 4 | 2 | - | - | 7 | 25 | 1 | 57 | 4 |
| | | | | Very High | >95th Percentile | > 91 | 12 | 5 | 2 | - | - | 8 | 23 | 1 | 59 | 4 |
| Site 18 | Central (Bangkok) | General site | 2013 | Very Low | <5th Percentile | < 10 | 1 | 1 | 0.1 | 0.1 | 0.2 | 0.4 | 77 | 5 | 15 | 1 |
| | | | | Low | <25th Percentile | < 23 | 8 | 1 | 1 | 0.1 | 0.1 | 1 | 76 | 5 | 16 | 1 |
| | | | | Moderate | 25th-75th Percentile | 23-56 | 38 | 1 | 2 | 0.1 | 0.1 | 2 | 59 | 4 | 29 | 2 |
| | | | | High | >75th Percentile | > 56 | 42 | 1 | 1 | - | - | 7 | 17 | 1 | 69 | 4 |
| | | | | Very High | >95th Percentile | > 95 | 13 | 1 | 1 | - | - | 7 | 12 | 1 | 75 | 4 |
| | | | 2014 | Very Low | <5th Percentile | < 8 | 0.5 | 0.3 | 0.1 | 0.3 | - | 0.3 | 77 | 6 | 16 | 0.4 |
| | | | | Low | <25th Percentile | < 20 | 6 | 0.3 | 0.2 | 0.2 | - | 1 | 75 | 5 | 18 | 1 |
| | | | | Moderate | 25th-75th Percentile | 20-51 | 37 | 1 | 1 | 0.1 | - | 2 | 62 | 3 | 29 | 2 |
| | | | | High | >75th Percentile | > 51 | 42 | 2 | 5 | - | - | 6 | 19 | 1 | 63 | 5 |
| | | | | Very High | >95th Percentile | > 92 | 14 | 2 | 5 | - | - | 7 | 15 | 0.2 | 68 | 4 |
| Site 19 | Central | General site | 2012 | Very Low | <5th Percentile | < 11 | 1 | 0.2 | - | 0.3 | - | 0.2 | 71 | 6 | 22 | 0.1 |
| | | | | Low | <25th Percentile | < 25 | 8 | 0.5 | - | 0.2 | - | 0.3 | 73 | 5 | 21 | 0.2 |
| | | | | Moderate | 25th-75th Percentile | 25-58 | 37 | 2 | 0.3 | 0.2 | - | 1 | 61 | 4 | 31 | 1 |
| | | | | High | >75th Percentile | > 58 | 42 | 5 | 1 | - | - | 4 | 28 | 1 | 60 | 1 |
| | | | | Very High | >95th Percentile | > 101 | 12 | 6 | 0.5 | - | - | 4 | 24 | 1 | 64 | 1 |
| Site 20 | Central | General site | 2011 | Very Low | <5th Percentile | < 5 | 0.4 | - | 1 | 0.2 | - | 2 | 64 | 5 | 27 | 1 |
| | | | | Low | <25th Percentile | < 16 | 7 | 0.1 | 2 | 0.2 | - | 2 | 61 | 5 | 28 | 1 |
| | | | | Moderate | 25th-75th Percentile | 16-39 | 39 | 0.2 | 4 | 0.1 | - | 4 | 50 | 4 | 35 | 3 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Cambodia | China | India | Indonesia | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | > 39 | 42 | 1 | 4 | 0.1 | - | 5 | 35 | 3 | 48 | 3 |
| | | | | Very High | >95th Percentile | > 63 | 12 | 1 | 3 | 0.1 | - | 5 | 34 | 3 | 50 | 3 |
| Site 21 | Central | General site | 2013 | Very Low | <5th Percentile | < 9 | 0.4 | 0.5 | 1 | 0.1 | 0.1 | 1 | 67 | 5 | 24 | 1 |
| | | | | Low | <25th Percentile | < 26 | 7 | 1 | 1 | 0.1 | 0.1 | 1 | 65 | 5 | 26 | 1 |
| | | | | Moderate | 25th-75th Percentile | 26-69 | 38 | 1 | 2 | 0.1 | 0.1 | 3 | 51 | 4 | 35 | 3 |
| | | | | High | >75th Percentile | > 69 | 43 | 2 | 1 | - | - | 5 | 29 | 1 | 58 | 3 |
| | | | | Very High | >95th Percentile | > 118 | 12 | 2 | 1 | - | - | 5 | 27 | 1 | 62 | 2 |
| | | | 2014 | Very Low | <5th Percentile | < 8 | 0.4 | 0.3 | 0.2 | 0.2 | 0.1 | 1 | 59 | 5 | 33 | 1 |
| | | | | Low | <25th Percentile | < 23 | 6 | 0.3 | 0.3 | 0.2 | - | 1 | 60 | 5 | 32 | 1 |
| | | | | Moderate | 25th-75th Percentile | 23-65 | 37 | 0.5 | 2 | 0.1 | - | 3 | 53 | 3 | 37 | 2 |
| | | | | High | >75th Percentile | > 65 | 44 | 1 | 3 | - | - | 5 | 42 | 1 | 44 | 4 |
| | | | | Very High | >95th Percentile | > 115 | 13 | 1 | 3 | - | - | 4 | 42 | 1 | 46 | 3 |
| Site 22 | Central | General site | 2012 | Very Low | <5th Percentile | < 10 | 1 | 0.2 | - | 0.2 | - | - | 84 | 5 | 11 | 0.2 |
| | | | | Low | <25th Percentile | < 18 | 8 | 0.4 | - | 0.2 | - | 0.1 | 82 | 4 | 12 | 0.3 |
| | | | | Moderate | 25th-75th Percentile | 18-42 | 38 | 2 | 0.4 | 0.2 | - | 1 | 62 | 4 | 29 | 1 |
| | | | | High | >75th Percentile | > 42 | 41 | 5 | 1 | - | - | 3 | 18 | 1 | 71 | 2 |
| | | | | Very High | >95th Percentile | > 75 | 12 | 4 | 1 | - | - | 3 | 11 | 0.3 | 79 | 2 |
| Site 23 | Central | General site | 2013 | Very Low | <5th Percentile | < 14 | 1 | 0.2 | - | - | 0.1 | 0.1 | 84 | 4 | 11 | 0.3 |
| | | | | Low | <25th Percentile | < 25 | 8 | 1 | 0.4 | 0.1 | 0.1 | 0.3 | 81 | 4 | 13 | 1 |
| | | | | Moderate | 25th-75th Percentile | 25-58 | 34 | 1 | 1 | 0.1 | 0.1 | 2 | 64 | 4 | 25 | 2 |
| | | | | High | >75th Percentile | > 58 | 44 | 1 | 2 | - | - | 8 | 14 | 0.4 | 68 | 5 |
| | | | | Very High | >95th Percentile | > 125 | 14 | 1 | 1 | - | - | 9 | 9 | 0.1 | 74 | 5 |
| | | | 2014 | Very Low | <5th Percentile | < 20 | 1 | 0.4 | - | 0.2 | - | 0.2 | 79 | 5 | 14 | 0.5 |
| | | | | Low | <25th Percentile | < 32 | 9 | 0.4 | 0.1 | 0.2 | - | 0.3 | 79 | 5 | 14 | 0.4 |
| | | | | Moderate | 25th-75th Percentile | 32-66 | 36 | 1 | 1 | 0.1 | - | 2 | 63 | 3 | 28 | 2 |
| | | | | High | >75th Percentile | > 66 | 40 | 3 | 7 | - | - | 6 | 19 | 0.4 | 61 | 5 |
| | | | | Very High | >95th Percentile | > 124 | 13 | 2 | 7 | - | - | 6 | 17 | 0.1 | 63 | 4 |
| Site 24 | Central | General site | 2012 | Very Low | <5th Percentile | < 10 | 1 | 1 | - | 0.1 | - | 0.3 | 80 | 3 | 15 | 0.4 |
| | | | | Low | <25th Percentile | < 23 | 7 | 1 | - | 0.2 | - | 0.5 | 76 | 4 | 18 | 0.4 |
| | | | | Moderate | 25th-75th Percentile | 23-56 | 38 | 2 | 1 | 0.1 | - | 2 | 62 | 3 | 30 | 1 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Cambodia | China | India | Indonesia | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | > 56 | 42 | 5 | 2 | - | - | 3 | 31 | 2 | 55 | 1 |
| | | | | Very High | >95th Percentile | > 99 | 13 | 6 | 2 | - | - | 3 | 27 | 3 | 59 | 1 |
| | | | 2013 | Very Low | <5th Percentile | < 11 | 1 | 3 | 0.5 | 0.1 | 0.4 | 1 | 69 | 4 | 20 | 1 |
| | | | | Low | <25th Percentile | < 22 | 8 | 2 | 1 | 0.1 | 0.2 | 1 | 72 | 4 | 18 | 1 |
| | | | | Moderate | 25th-75th Percentile | 22-51 | 36 | 1 | 2 | 0.1 | 0.1 | 2 | 61 | 4 | 28 | 2 |
| | | | | High | >75th Percentile | > 51 | 42 | 1 | 1 | - | - | 7 | 16 | 1 | 70 | 4 |
| | | | | Very High | >95th Percentile | > 96 | 13 | 0.4 | 1 | - | - | 7 | 10 | 0.4 | 78 | 3 |
| | | | 2014 | Very Low | <5th Percentile | < 12 | 1 | 0.2 | - | 0.4 | - | 0.5 | 76 | 6 | 17 | 0.3 |
| | | | | Low | <25th Percentile | < 23 | 8 | 0.2 | 0.1 | 0.3 | - | 1 | 75 | 5 | 18 | 0.4 |
| | | | | Moderate | 25th-75th Percentile | 23-49 | 36 | 1 | 1 | 0.1 | - | 2 | 63 | 3 | 28 | 2 |
| | | | | High | >75th Percentile | > 49 | 42 | 3 | 5 | - | - | 5 | 22 | 1 | 60 | 4 |
| | | | | Very High | >95th Percentile | > 94 | 14 | 3 | 5 | - | - | 5 | 19 | 0.3 | 65 | 3 |
| | | | 2015 | Very Low | <5th Percentile | < 10 | 1 | 0.1 | - | 0.3 | - | 0.1 | 75 | 7 | 18 | - |
| | | | | Low | <25th Percentile | < 20 | 7 | 0.3 | 0.1 | 0.2 | - | 0.4 | 75 | 6 | 17 | 0.2 |
| | | | | Moderate | 25th-75th Percentile | 20-45 | 38 | 2 | 1 | 0.1 | - | 3 | 62 | 4 | 27 | 2 |
| | | | | High | >75th Percentile | > 45 | 42 | 5 | 1 | - | - | 7 | 24 | 2 | 58 | 3 |
| | | | | Very High | >95th Percentile | > 79 | 12 | 5 | 1 | - | - | 7 | 20 | 2 | 62 | 3 |
| Site 25 | Central | General site | 2012 | Very Low | <5th Percentile | < 15 | 1 | 0.3 | - | 0.2 | - | - | 84 | 4 | 11 | 0.1 |
| | | | | Low | <25th Percentile | < 27 | 8 | 0.3 | - | 0.2 | - | - | 83 | 5 | 12 | 0.1 |
| | | | | Moderate | 25th-75th Percentile | 27-63 | 37 | 2 | 0.4 | 0.2 | - | 1 | 64 | 3 | 28 | 1 |
| | | | | High | >75th Percentile | > 63 | 42 | 7 | 1 | - | - | 4 | 25 | 1 | 61 | 2 |
| | | | | Very High | >95th Percentile | > 110 | 12 | 7 | 1 | - | - | 4 | 17 | 1 | 68 | 2 |
| | | | 2013 | Very Low | <5th Percentile | < 22 | 1 | 1 | 0.3 | - | 0.1 | 1 | 79 | 4 | 13 | 0.5 |
| | | | | Low | <25th Percentile | < 39 | 9 | 1 | 1 | 0.1 | 0.1 | 1 | 78 | 4 | 14 | 1 |
| | | | | Moderate | 25th-75th Percentile | 39-81 | 38 | 1 | 2 | 0.1 | 0.1 | 2 | 63 | 4 | 26 | 2 |
| | | | | High | >75th Percentile | > 81 | 39 | 1 | 2 | - | - | 8 | 18 | 1 | 66 | 4 |
| | | | | Very High | >95th Percentile | > 137 | 12 | 1 | 1 | - | - | 9 | 12 | 0.2 | 72 | 5 |
| Site 26 | Central | General site | 2013 | Very Low | <5th Percentile | < 8 | 0.4 | 1 | 1 | 0.1 | - | 1 | 77 | 5 | 14 | 1 |
| | | | | Low | <25th Percentile | < 20 | 6 | 1 | 1 | 0.1 | 0.1 | 1 | 77 | 5 | 15 | 1 |
| | | | | Moderate | 25th-75th Percentile | 20-56 | 34 | 2 | 2 | 0.1 | 0.1 | 3 | 61 | 4 | 27 | 2 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Cambodia | China | India | Indonesia | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | > 56 | 45 | 1 | 2 | - | - | 8 | 15 | 0.5 | 68 | 5 |
| | | | | Very High | >95th Percentile | > 110 | 14 | 1 | 2 | - | - | 8 | 10 | 0.1 | 75 | 4 |
| | | | 2014 | Very Low | <5th Percentile | < 9 | 0.5 | 1 | 0.2 | 0.2 | - | 1 | 80 | 5 | 13 | 1 |
| | | | | Low | <25th Percentile | < 23 | 6 | 1 | 0.2 | 0.2 | - | 1 | 77 | 5 | 16 | 1 |
| | | | | Moderate | 25th-75th Percentile | 23-57 | 35 | 1 | 2 | 0.1 | - | 2 | 63 | 3 | 27 | 2 |
| | | | | High | >75th Percentile | > 57 | 44 | 5 | 6 | - | - | 6 | 23 | 1 | 54 | 5 |
| | | | | Very High | >95th Percentile | > 109 | 14 | 6 | 7 | - | - | 6 | 18 | 0.1 | 58 | 5 |
| Site 27 | Central | | 2014 | Very Low | <5th Percentile | < 13 | 0.5 | 1 | - | 0.2 | - | 1 | 62 | 6 | 30 | 0.4 |
| | | | | Low | <25th Percentile | < 33 | 8 | 0.5 | 0.1 | 0.1 | - | 1 | 64 | 6 | 29 | 0.4 |
| | | | | Moderate | 25th-75th Percentile | 33-73 | 39 | 1 | 1 | 0.1 | - | 2 | 63 | 4 | 29 | 2 |
| | | | | High | >75th Percentile | > 73 | 41 | 4 | 5 | - | - | 6 | 23 | 1 | 58 | 4 |
| | | | | Very High | >95th Percentile | > 127 | 13 | 5 | 5 | - | - | 6 | 19 | 1 | 62 | 3 |
| Site 28 | Central | General site | 2014 | Very Low | <5th Percentile | < 9 | 0.4 | 1 | - | 0.2 | - | 1 | 77 | 7 | 13 | 0.4 |
| | | | | Low | <25th Percentile | < 21 | 5 | 1 | - | 0.2 | - | 0.4 | 78 | 6 | 14 | 0.3 |
| | | | | Moderate | 25th-75th Percentile | 21-66 | 31 | 1 | 1 | 0.1 | - | 1 | 63 | 4 | 28 | 1 |
| | | | | High | >75th Percentile | > 66 | 47 | 3 | 6 | - | - | 7 | 17 | 0.5 | 62 | 5 |
| | | | | Very High | >95th Percentile | > 146 | 16 | 3 | 6 | - | - | 7 | 15 | - | 64 | 5 |
| Site 47 | Central | General site | 2015 | Very Low | <5th Percentile | < 8 | 0.4 | 1 | - | 0.3 | - | 1 | 79 | 5 | 14 | 0.2 |
| | | | | Low | <25th Percentile | < 19 | 6 | 1 | - | 0.3 | - | 0.3 | 80 | 7 | 13 | 0.1 |
| | | | | Moderate | 25th-75th Percentile | 19-57 | 37 | 1 | 0.4 | 0.1 | - | 2 | 60 | 6 | 30 | 1 |
| | | | | High | >75th Percentile | > 57 | 44 | 5 | 2 | - | - | 7 | 21 | 2 | 60 | 3 |
| | | | | Very High | >95th Percentile | > 105 | 13 | 6 | 2 | - | - | 8 | 19 | 2 | 61 | 3 |
| Site 49 | Central | General site | 2011 | Very Low | <5th Percentile | < 21 | 1 | 3 | 0.2 | 0.1 | - | 1 | 56 | 5 | 34 | 1 |
| | | | | Low | <25th Percentile | < 47 | 7 | 2 | 1 | 0.1 | - | 1 | 58 | 5 | 32 | 1 |
| | | | | Moderate | 25th-75th Percentile | 47-124 | 37 | 0.3 | 7 | 0.1 | - | 6 | 36 | 3 | 44 | 4 |
| | | | | High | >75th Percentile | > 124 | 42 | 1 | 4 | - | - | 7 | 25 | 3 | 56 | 4 |
| | | | | Very High | >95th Percentile | > 218 | 13 | 1 | 3 | - | - | 8 | 23 | 2 | 59 | 4 |
| | | | 2012 | Very Low | <5th Percentile | < 22 | 1 | 0.1 | 0.2 | 0.1 | - | 0.2 | 64 | 5 | 30 | 0.4 |
| | | | | Low | <25th Percentile | < 48 | 6 | 0.2 | 1 | 0.1 | - | 1 | 64 | 5 | 29 | 1 |
| | | | | Moderate | 25th-75th Percentile | 48-145 | 36 | 1 | 2 | 0.1 | - | 3 | 42 | 3 | 47 | 2 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Country Contribution (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | Cambodia | China | India | Indonesia | Laos | Marine | Myanmar | Thailand | Vietnam |
| | | | | High | >75th Percentile | > 145 | 45 | 3 | 1 | - | - | 5 | 17 | 1 | 71 | 2 |
| | | | | Very High | >95th Percentile | > 268 | 13 | 3 | 1 | - | - | 5 | 14 | 1 | 75 | 2 |
| | | | 2014 | Very Low | <5th Percentile | < 19 | 1 | - | 0.5 | 0.1 | - | 0.3 | 59 | 7 | 32 | 0.3 |
| | | | | Low | <25th Percentile | < 44 | 6 | 0.1 | 1 | 0.1 | - | 1 | 61 | 6 | 31 | 1 |
| | | | | Moderate | 25th-75th Percentile | 44-124 | 36 | 1 | 4 | 0.1 | - | 4 | 44 | 3 | 41 | 4 |
| | | | | High | >75th Percentile | > 124 | 43 | 1 | 4 | - | - | 7 | 19 | 1 | 63 | 5 |
| | | | | Very High | >95th Percentile | > 234 | 14 | 1 | 3 | - | - | 8 | 16 | 1 | 67 | 4 |
| | | | 2015 | Very Low | <5th Percentile | < 23 | 1 | - | - | 0.1 | - | 0.1 | 64 | 5 | 30 | - |
| | | | | Low | <25th Percentile | < 45 | 7 | - | 0.2 | 0.2 | - | 0.3 | 63 | 5 | 30 | 0.2 |
| | | | | Moderate | 25th-75th Percentile | 45-124 | 34 | 1 | 3 | 0.1 | - | 5 | 44 | 3 | 41 | 3 |
| | | | | High | >75th Percentile | > 124 | 45 | 2 | 2 | - | - | 7 | 20 | 3 | 63 | 3 |
| | | | | Very High | >95th Percentile | > 256 | 14 | 2 | 2 | - | - | 6 | 17 | 5 | 66 | 3 |
| Site 51 | Central | | 2014 | Very Low | <5th Percentile | < 14 | 1 | 1 | 0.3 | 0.1 | - | 0.3 | 64 | 6 | 29 | 0.4 |
| | | | | Low | <25th Percentile | < 28 | 7 | 0.4 | 0.2 | 0.1 | - | 1 | 63 | 6 | 30 | 0.4 |
| | | | | Moderate | 25th-75th Percentile | 28-72 | 37 | 0.4 | 2 | 0.1 | - | 3 | 51 | 3 | 38 | 2 |
| | | | | High | >75th Percentile | > 72 | 42 | 0.4 | 6 | - | - | 9 | 17 | 1 | 60 | 6 |
| | | | | Very High | >95th Percentile | > 131 | 13 | 0.3 | 5 | - | - | 10 | 12 | 1 | 67 | 6 |

**Table S15:** Hourly contribution concentrations at monitoring sites across central Thailand in different years

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| Site 2 | Central (Bangkok) | General site | 2014 | Very Low | <5th Percentile | < 20 | 1 | 10 | 7 | 8 | 15 | 12 | 5 | 1 | 0.5 | 1 | 0.2 | 2 | 2 | 1 | 1 | 1 | 3 | 8 | 8 | 1 | 1 | 4 | 2 | 2 | 5 |
| | | | | Low | <25th Percentile | < 31 | 10 | 8 | 6 | 7 | 11 | 9 | 5 | 2 | 1 | 1 | 1 | 2 | 3 | 2 | 2 | 2 | 4 | 7 | 6 | 2 | 2 | 4 | 4 | 4 | 5 |
| | | | | Moderate | 25th-75th Percentile | 31-62 | 36 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 62 | 40 | 4 | 4 | 3 | 4 | 4 | 5 | 5 | 6 | 6 | 6 | 5 | 4 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 5 | 5 | 5 |
| | | | | Very High | >95th Percentile | > 109 | 13 | 4 | 4 | 4 | 4 | 5 | 5 | 6 | 6 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 2 | 2 | 3 | 3 | 4 | 6 | 6 | 6 |
| Site 6 | Central (Bangkok) | General site | 2012 | Very Low | <5th Percentile | < 5 | 0.5 | 2 | 1 | 3 | 3 | 3 | 1 | 0.3 | 0.5 | 7 | 17 | 22 | 13 | 12 | 5 | 5 | 1 | 0.3 | - | - | 1 | 1 | 1 | 2 | 1 |
| | | | | Low | <25th Percentile | < 14 | 6 | 3 | 3 | 4 | 4 | 4 | 3 | 2 | 2 | 5 | 11 | 12 | 11 | 9 | 6 | 4 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 2 |
| | | | | Moderate | 25th-75th Percentile | 14-34 | 39 | 4 | 5 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 3 | 3 | 3 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 5 |
| | | | | High | >75th Percentile | > 34 | 42 | 5 | 4 | 4 | 2 | 3 | 5 | 4 | 5 | 3 | 1 | 0.5 | 0.5 | 1 | 3 | 2 | 7 | 6 | 3 | 10 | 8 | 6 | 7 | 6 | 5 |
| | | | | Very High | >95th Percentile | > 56 | 12 | 5 | 4 | 4 | 2 | 3 | 6 | 3 | 4 | 2 | 1 | 0.3 | 0.2 | 0.5 | 3 | 1 | 8 | 6 | 3 | 10 | 9 | 6 | 8 | 7 | 5 |
| | | | 2014 | Very Low | <5th Percentile | < 16 | 1 | 8 | 10 | 10 | 20 | 14 | 5 | 2 | 0.2 | 3 | 2 | 3 | 0.4 | 2 | 1 | 2 | 5 | 3 | 1 | 1 | 1 | 1 | 1 | 3 | 4 |
| | | | | Low | <25th Percentile | < 26 | 8 | 6 | 8 | 8 | 13 | 10 | 5 | 2 | 1 | 2 | 2 | 4 | 2 | 3 | 3 | 4 | 5 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 4 |
| | | | | Moderate | 25th-75th Percentile | 26-57 | 36 | 4 | 3 | 3 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 57 | 41 | 5 | 4 | 4 | 4 | 4 | 6 | 6 | 7 | 7 | 7 | 5 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 5 | 5 | 6 | 6 | 6 |
| | | | | Very High | >95th Percentile | > 108 | 13 | 6 | 4 | 5 | 5 | 4 | 7 | 7 | 7 | 7 | 8 | 6 | 2 | 1 | 1 | 0.4 | 0.1 | 0.1 | 1 | 1 | 4 | 4 | 7 | 7 | 6 |
| | | | 2015 | Very Low | <5th Percentile | < 12 | 1 | 6 | 15 | 12 | 11 | 17 | 7 | 2 | 1 | 0.5 | 1 | 1 | 1 | 2 | 2 | 3 | 1 | 1 | 0.4 | 2 | 3 | 2 | 1 | 2 | 5 |
| | | | | Low | <25th Percentile | < 22 | 8 | 5 | 10 | 8 | 8 | 10 | 6 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 5 |
| | | | | Moderate | 25th-75th Percentile | 22-50 | 37 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 50 | 41 | 4 | 4 | 4 | 3 | 3 | 4 | 5 | 9 | 9 | 8 | 4 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 5 | 8 | 6 | 5 |
| | | | | Very High | >95th Percentile | > 90 | 13 | 3 | 3 | 4 | 3 | 3 | 4 | 5 | 11 | 10 | 10 | 4 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 5 | 10 | 7 | 5 |
| Site 7 | Central (Bangkok) | General site | 2012 | Very Low | <5th Percentile | < 17 | 1 | 4 | 10 | 10 | 9 | 8 | 6 | 4 | 1 | 0.3 | 1 | 1 | 3 | 2 | 2 | 3 | 2 | 3 | 9 | 8 | 2 | 2 | 3 | 6 | 3 |
| | | | | Low | <25th Percentile | < 27 | 9 | 4 | 8 | 8 | 8 | 7 | 6 | 5 | 2 | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 7 | 6 | 2 | 2 | 3 | 5 | 3 |
| | | | | Moderate | 25th-75th Percentile | 27-55 | 40 | 4 | 4 | 4 | 3 | 3 | 3 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 55 | 39 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 5 | 5 | 5 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 6 | 7 | 7 | 7 | 5 |
| | | | | Very High | >95th Percentile | > 91 | 11 | 4 | 4 | 4 | 5 | 5 | 3 | 3 | 5 | 5 | 5 | 5 | 4 | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 6 | 7 | 7 | 7 | 4 |
| Site 8 | Central (Bangkok) | General site | 2014 | Very Low | <5th Percentile | < 14 | 1 | 8 | 11 | 14 | 9 | 10 | 6 | 2 | 1 | 1 | 1 | 0.5 | 1 | 1 | 6 | 6 | 2 | 3 | 0.5 | 1 | 2 | 2 | 3 | 2 | 6 |
| | | | | Low | <25th Percentile | < 27 | 8 | 6 | 8 | 10 | 7 | 8 | 5 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 5 | 5 | 3 | 3 | 2 | 2 | 3 | 3 | 4 | 3 | 5 |
| | | | | Moderate | 25th-75th Percentile | 27-59 | 36 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 59 | 41 | 5 | 4 | 5 | 4 | 4 | 5 | 8 | 5 | 6 | 6 | 5 | 4 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 4 | 3 | 5 | 6 | 5 |
| | | | | Very High | >95th Percentile | > 109 | 13 | 5 | 5 | 6 | 5 | 5 | 5 | 9 | 5 | 7 | 6 | 5 | 3 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 4 | 3 | 5 | 7 | 5 |
| Site 9 | Central (Bangkok) | General site | 2013 | Very Low | <5th Percentile | < 5 | 1 | 1 | 1 | 8 | 8 | 4 | 2 | 3 | 1 | 2 | 1 | 8 | 6 | - | 1 | 2 | 9 | 4 | 1 | 10 | 8 | 4 | 1 | 5 | 8 |
| | | | | Low | <25th Percentile | < 11 | 6 | 1 | 1 | 5 | 6 | 5 | 4 | 3 | 2 | 4 | 5 | 6 | 5 | 1 | 1 | 3 | 6 | 5 | 4 | 6 | 6 | 5 | 5 | 5 | 5 |
| | | | | Moderate | 25th-75th Percentile | 11-26 | 38 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 4 |
| | | | | High | >75th Percentile | > 26 | 43 | 11 | 9 | 5 | 3 | 4 | 3 | 8 | 6 | 4 | 4 | 2 | 1 | 3 | 4 | 3 | 2 | 1 | 1 | 2 | 3 | 4 | 7 | 6 | 5 |
| | | | | Very High | >95th Percentile | > 44 | 13 | 12 | 10 | 5 | 2 | 4 | 3 | 9 | 6 | 3 | 4 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 0.2 | 1 | 2 | 5 | 9 | 8 | 6 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| Site 12 | Central (Bangkok) | Roadside site | 2011 | Very Low | <5th Percentile | < 24 | 1 | 7 | 6 | 7 | 15 | 20 | 8 | 9 | 2 | 1 | 1 | 1 | 1 | 1 | 6 | 1 | 1 | 1 | 0.5 | 2 | 1 | 2 | 2 | 3 | 2 |
| | | | | Low | <25th Percentile | < 39 | 11 | 6 | 6 | 7 | 11 | 14 | 7 | 7 | 3 | 1 | 1 | 2 | 2 | 2 | 6 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 4 |
| | | | | Moderate | 25th-75th Percentile | 39-72 | 41 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 72 | 36 | 5 | 4 | 3 | 2 | 2 | 5 | 7 | 9 | 7 | 5 | 5 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 5 | 7 | 7 |
| | | | | Very High | >95th Percentile | > 106 | 10 | 5 | 3 | 2 | 2 | 1 | 5 | 8 | 10 | 8 | 5 | 5 | 3 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 4 | 9 | 9 |
| | | | 2013 | Very Low | <5th Percentile | < 28 | 1 | 7 | 10 | 18 | 11 | 9 | 5 | 5 | 1 | 0.5 | 1 | 1 | 1 | 1 | 2 | 2 | 4 | 2 | 7 | 1 | 2 | 1 | 2 | 2 | 4 |
| | | | | Low | <25th Percentile | < 43 | 11 | 6 | 8 | 12 | 9 | 8 | 5 | 4 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 4 | 3 | 6 | 3 | 3 | 2 | 3 | 3 | 5 |
| | | | | Moderate | 25th-75th Percentile | 43-84 | 40 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 5 | 5 | 5 | 4 | 5 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 84 | 38 | 4 | 4 | 3 | 3 | 2 | 5 | 6 | 7 | 10 | 7 | 4 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 5 | 5 | 6 | 6 |
| | | | | Very High | >95th Percentile | > 134 | 11 | 5 | 4 | 3 | 3 | 2 | 6 | 7 | 8 | 12 | 8 | 4 | 1 | 1 | 1 | 0.4 | 1 | 1 | 2 | 2 | 2 | 6 | 5 | 7 | 7 |
| Site 14 | Central (Bangkok) | Roadside site | 2015 | Very Low | <5th Percentile | < 8 | 1 | 4 | 8 | 8 | 7 | 11 | 8 | 4 | 3 | 2 | 1 | 2 | 2 | 2 | 4 | 7 | 4 | 4 | 3 | 2 | 2 | 2 | 3 | 3 | 3 |
| | | | | Low | <25th Percentile | < 12 | 9 | 5 | 7 | 7 | 7 | 9 | 8 | 5 | 4 | 2 | 1 | 2 | 2 | 2 | 3 | 5 | 4 | 5 | 3 | 2 | 3 | 2 | 3 | 4 | 4 |
| | | | | Moderate | 25th-75th Percentile | 12-23 | 41 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 23 | 38 | 5 | 3 | 7 | 3 | 4 | 3 | 4 | 7 | 12 | 8 | 5 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 4 | 5 | 9 | 6 |
| | | | | Very High | >95th Percentile | > 36 | 11 | 5 | 3 | 8 | 3 | 4 | 3 | 4 | 8 | 14 | 8 | 4 | 1 | 1 | 0.3 | 1 | 1 | 1 | 1 | 1 | 2 | 4 | 6 | 10 | 7 |
| Site 15 | Central (Bangkok) | Roadside site | 2014 | Very Low | <5th Percentile | < 3 | 0.4 | 2 | 4 | 11 | 5 | 7 | 1 | 3 | 1 | 10 | 21 | 14 | 9 | 2 | 1 | 1 | 0.4 | 0.1 | 1 | 3 | 1 | 4 | 0.1 | 1 | 2 |
| | | | | Low | <25th Percentile | < 10 | 5 | 3 | 2 | 8 | 7 | 5 | 3 | 2 | 3 | 6 | 9 | 11 | 9 | 5 | 2 | 2 | 1 | 2 | 2 | 4 | 4 | 3 | 2 | 2 | 3 |
| | | | | Moderate | 25th-75th Percentile | 10-28 | 36 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 2 | 3 | 5 | 4 | 6 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 28 | 44 | 7 | 8 | 7 | 3 | 3 | 5 | 7 | 9 | 5 | 1 | 1 | 1 | 1 | 3 | 2 | 1 | 3 | 2 | 2 | 4 | 4 | 5 | 8 | 7 |
| | | | | Very High | >95th Percentile | > 51 | 14 | 7 | 9 | 8 | 3 | 3 | 4 | 7 | 11 | 6 | 1 | 0.3 | 1 | 0.3 | 1 | 1 | 1 | 4 | 2 | 2 | 4 | 3 | 5 | 9 | 7 |
| Site 16 | Central (Bangkok) | Roadside site | 2013 | Very Low | <5th Percentile | < 13 | 1 | 16 | 19 | 14 | 10 | 1 | 2 | - | 0.2 | 0.3 | 1 | 1 | 2 | 4 | 3 | 4 | 3 | 2 | 1 | 0.4 | 0.4 | 0.4 | 2 | 4 | 11 |
| | | | | Low | <25th Percentile | < 31 | 7 | 11 | 12 | 10 | 8 | 3 | 3 | 1 | 1 | 1 | 2 | 3 | 4 | 5 | 5 | 5 | 4 | 3 | 2 | 1 | 1 | 1 | 3 | 5 | 9 |
| | | | | Moderate | 25th-75th Percentile | 31-78 | 39 | 2 | 2 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 3 | 3 |
| | | | | High | >75th Percentile | > 78 | 41 | 2 | 3 | 2 | 3 | 4 | 7 | 8 | 8 | 7 | 3 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 4 | 7 | 9 | 9 | 7 | 5 | 4 |
| | | | | Very High | >95th Percentile | > 130 | 12 | 2 | 3 | 2 | 2 | 4 | 8 | 9 | 8 | 7 | 2 | 2 | 1 | 0.3 | 0.2 | 0.2 | 1 | 1 | 3 | 7 | 10 | 11 | 9 | 6 | 4 |
| | | | 2015 | Very Low | <5th Percentile | < 8 | 0.4 | 23 | 24 | 15 | 5 | 2 | - | - | 0.4 | 0.3 | - | 1 | 3 | 4 | 4 | 2 | 1 | 0.2 | - | - | - | 0.2 | 1 | 4 | 12 |
| | | | | Low | <25th Percentile | < 23 | 6 | 12 | 12 | 11 | 6 | 3 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 5 | 5 | 4 | 4 | 2 | 1 | 1 | 1 | 1 | 3 | 6 | 9 |
| | | | | Moderate | 25th-75th Percentile | 23-65 | 38 | 2 | 2 | 2 | 4 | 5 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 5 | 4 | 3 | 4 | 4 | 3 | 2 |
| | | | | High | >75th Percentile | > 65 | 43 | 3 | 2 | 1 | 2 | 4 | 6 | 8 | 6 | 4 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 5 | 9 | 11 | 10 | 9 | 6 | 4 |
| | | | | Very High | >95th Percentile | > 110 | 12 | 2 | 1 | 1 | 1 | 3 | 6 | 9 | 6 | 3 | 2 | 1 | 0.1 | 0.2 | 1 | 0.1 | 1 | 1 | 3 | 9 | 12 | 13 | 12 | 8 | 4 |
| Site 17 | Central (Bangkok) | General site | 2015 | Very Low | <5th Percentile | < 13 | 1 | 9 | 18 | 9 | 14 | 13 | 8 | 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0.3 | 0.4 | 1 | 2 | 2 | 3 | 6 |
| | | | | Low | <25th Percentile | < 24 | 9 | 7 | 12 | 7 | 10 | 9 | 7 | 4 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 2 | 1 | 2 | 2 | 3 | 3 | 4 | 6 |
| | | | | Moderate | 25th-75th Percentile | 24-50 | 37 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 3 | 3 |
| | | | | High | >75th Percentile | > 50 | 41 | 4 | 4 | 3 | 5 | 4 | 4 | 5 | 8 | 8 | 6 | 4 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 5 | 7 | 6 | 6 |
| | | | | Very High | >95th Percentile | > 91 | 12 | 3 | 3 | 2 | 5 | 4 | 5 | 5 | 9 | 9 | 7 | 4 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 5 | 8 | 7 | 6 |
| Site 18 | Central (Bangkok) | General site | 2013 | Very Low | <5th Percentile | < 10 | 1 | 6 | 8 | 8 | 7 | 4 | 2 | 3 | 3 | 4 | 2 | 1 | 1 | 3 | 5 | 9 | 6 | 5 | 3 | 2 | 2 | 2 | 2 | 4 | 7 |
| | | | | Low | <25th Percentile | < 23 | 8 | 5 | 7 | 7 | 6 | 5 | 4 | 3 | 2 | 4 | 3 | 2 | 3 | 4 | 5 | 6 | 5 | 5 | 3 | 2 | 3 | 3 | 3 | 4 | 6 |
| | | | | Moderate | 25th-75th Percentile | 23-56 | 38 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 3 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| | | | | High | >75th Percentile | > 56 | 42 | 6 | 5 | 4 | 3 | 3 | 3 | 5 | 9 | 8 | 7 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 5 | 6 | 8 | 6 |
| | | | | Very High | >95th Percentile | > 95 | 13 | 7 | 6 | 4 | 3 | 3 | 2 | 5 | 11 | 10 | 8 | 3 | 1 | 1 | 0.5 | 2 | 0.3 | 1 | 1 | 1 | 2 | 5 | 7 | 10 | 7 |
| | | | 2014 | Very Low | <5th Percentile | < 8 | 0.5 | 7 | 10 | 11 | 7 | 5 | 4 | 5 | 0.4 | 1 | 3 | 4 | 3 | 4 | 2 | 2 | 1 | 1 | 0.4 | 1 | 2 | 4 | 9 | 9 | 4 |
| | | | | Low | <25th Percentile | < 20 | 6 | 6 | 7 | 8 | 7 | 6 | 5 | 4 | 2 | 2 | 4 | 5 | 4 | 4 | 3 | 2 | 1 | 1 | 1 | 2 | 3 | 4 | 6 | 7 | 5 |
| | | | | Moderate | 25th-75th Percentile | 20-51 | 37 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 4 | 3 | 4 |
| | | | | High | >75th Percentile | > 51 | 42 | 6 | 4 | 4 | 4 | 4 | 3 | 5 | 10 | 8 | 7 | 4 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 3 | 4 | 7 | 5 |
| | | | | Very High | >95th Percentile | > 92 | 14 | 6 | 4 | 5 | 4 | 4 | 4 | 6 | 12 | 9 | 8 | 5 | 3 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 4 | 8 | 5 |
| Site 19 | Central | General site | 2012 | Very Low | <5th Percentile | < 11 | 1 | 5 | 8 | 7 | 8 | 3 | 2 | 0.4 | 0.4 | 18 | 8 | 3 | 2 | 1 | 1 | 2 | 1 | 3 | 1 | 2 | 2 | 5 | 5 | 7 | 5 |
| | | | | Low | <25th Percentile | < 25 | 8 | 6 | 7 | 7 | 7 | 5 | 4 | 2 | 2 | 10 | 6 | 4 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 4 | 5 | 6 | 5 |
| | | | | Moderate | 25th-75th Percentile | 25-58 | 37 | 4 | 3 | 3 | 4 | 4 | 4 | 5 | 4 | 3 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 58 | 42 | 3 | 4 | 5 | 3 | 3 | 4 | 5 | 10 | 6 | 4 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 4 | 6 | 7 | 6 | 6 | 5 |
| | | | | Very High | >95th Percentile | > 101 | 12 | 3 | 5 | 6 | 4 | 3 | 5 | 5 | 12 | 6 | 4 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 6 | 8 | 7 | 7 | 5 |
| Site 20 | Central | General site | 2011 | Very Low | <5th Percentile | < 5 | 0.4 | 2 | 1 | 1 | 2 | 1 | 0.2 | - | 6 | 19 | 26 | 12 | 14 | 8 | 2 | 3 | 1 | 0.2 | - | - | 0.2 | - | 0.2 | 1 | 2 |
| | | | | Low | <25th Percentile | < 16 | 7 | 4 | 3 | 4 | 5 | 4 | 3 | 3 | 6 | 9 | 12 | 9 | 10 | 7 | 3 | 3 | 2 | 1 | 1 | 0.4 | 1 | 1 | 2 | 3 | 5 |
| | | | | Moderate | 25th-75th Percentile | 16-39 | 39 | 4 | 3 | 5 | 4 | 4 | 5 | 5 | 4 | 3 | 2 | 4 | 3 | 4 | 4 | 5 | 6 | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 4 |
| | | | | High | >75th Percentile | > 39 | 42 | 3 | 8 | 2 | 2 | 2 | 2 | 2 | 8 | 7 | 2 | 2 | 1 | 1 | 5 | 2 | 2 | 3 | 5 | 9 | 11 | 9 | 6 | 4 | 2 |
| | | | | Very High | >95th Percentile | > 63 | 12 | 2 | 9 | 2 | 1 | 1 | 2 | 2 | 10 | 9 | 2 | 2 | 1 | 1 | 5 | 2 | 2 | 2 | 3 | 8 | 13 | 10 | 7 | 4 | 2 |
| Site 21 | Central | General site | 2013 | Very Low | <5th Percentile | < 9 | 0.4 | 3 | 3 | 4 | 4 | 6 | 6 | 4 | 1 | 0.3 | 0.5 | 2 | 8 | 9 | 12 | 5 | 3 | 1 | 2 | 5 | 5 | 4 | 7 | 4 | 3 |
| | | | | Low | <25th Percentile | < 26 | 7 | 4 | 3 | 4 | 5 | 6 | 6 | 4 | 1 | 1 | 1 | 4 | 6 | 7 | 7 | 5 | 3 | 3 | 3 | 5 | 4 | 4 | 5 | 4 | 4 |
| | | | | Moderate | 25th-75th Percentile | 26-69 | 38 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 69 | 43 | 6 | 6 | 6 | 3 | 4 | 2 | 2 | 6 | 6 | 6 | 4 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 4 | 6 | 7 | 6 | 6 | 6 |
| | | | | Very High | >95th Percentile | > 118 | 12 | 7 | 7 | 7 | 3 | 4 | 2 | 1 | 5 | 7 | 7 | 4 | 1 | 0.3 | 1 | 1 | 2 | 1 | 3 | 4 | 6 | 9 | 8 | 6 | 7 |
| | | | 2014 | Very Low | <5th Percentile | < 8 | 0.4 | 3 | 4 | 5 | 6 | 4 | 3 | 1 | 1 | 0.4 | 2 | 5 | 5 | 7 | 13 | 9 | 6 | 4 | 4 | 4 | 5 | 2 | 1 | 2 | 3 |
| | | | | Low | <25th Percentile | < 23 | 6 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 2 | 2 | 2 | 4 | 5 | 6 | 7 | 6 | 5 | 6 | 5 | 4 | 4 | 3 | 3 | 3 | 3 |
| | | | | Moderate | 25th-75th Percentile | 23-65 | 37 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 3 | 3 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 5 | 4 |
| | | | | High | >75th Percentile | > 65 | 44 | 5 | 6 | 6 | 6 | 4 | 5 | 6 | 6 | 4 | 3 | 2 | 1 | 1 | 2 | 3 | 2 | 1 | 1 | 3 | 4 | 7 | 8 | 5 | 6 |
| | | | | Very High | >95th Percentile | > 115 | 13 | 6 | 7 | 7 | 6 | 4 | 5 | 7 | 7 | 2 | 2 | 2 | 1 | 0.4 | 1 | 3 | 2 | 1 | 0.4 | 2 | 4 | 7 | 10 | 6 | 7 |
| Site 22 | Central | General site | 2012 | Very Low | <5th Percentile | < 10 | 1 | 4 | 6 | 10 | 9 | 5 | 2 | 1 | - | 2 | 4 | 8 | 5 | 4 | 8 | 6 | 4 | 4 | 1 | 3 | 1 | 5 | 3 | 2 | 3 |
| | | | | Low | <25th Percentile | < 18 | 8 | 4 | 6 | 8 | 8 | 5 | 3 | 2 | 1 | 1 | 4 | 6 | 5 | 4 | 7 | 5 | 4 | 4 | 3 | 4 | 2 | 4 | 3 | 2 | 3 |
| | | | | Moderate | 25th-75th Percentile | 18-42 | 38 | 4 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 42 | 41 | 6 | 4 | 5 | 4 | 4 | 3 | 4 | 5 | 8 | 5 | 3 | 2 | 2 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 4 | 6 | 7 | 8 | 8 |
| | | | | Very High | >95th Percentile | > 75 | 12 | 7 | 3 | 6 | 5 | 4 | 3 | 4 | 5 | 9 | 4 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 3 | 1 | 4 | 6 | 8 | 9 | 10 |
| Site 23 | Central | General site | 2013 | Very Low | <5th Percentile | < 14 | 1 | 3 | 2 | 3 | 3 | 1 | 2 | 1 | 1 | 3 | 2 | 2 | 1 | 4 | 15 | 5 | 14 | 3 | 5 | 14 | 2 | 1 | 4 | 5 | 4 |
| | | | | Low | <25th Percentile | < 25 | 8 | 4 | 3 | 4 | 4 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 4 | 10 | 5 | 9 | 4 | 5 | 10 | 3 | 3 | 4 | 5 | 4 |
| | | | | Moderate | 25th-75th Percentile | 25-58 | 34 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 58 | 44 | 6 | 4 | 4 | 4 | 3 | 4 | 5 | 5 | 7 | 7 | 5 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 5 | 6 | 6 | 5 |
| | | | | Very High | >95th Percentile | > 125 | 14 | 7 | 4 | 4 | 4 | 3 | 4 | 6 | 6 | 8 | 9 | 6 | 2 | 1 | 0.4 | 1 | 1 | 1 | 2 | 2 | 3 | 5 | 7 | 8 | 7 |
| | | | 2014 | Very Low | <5th Percentile | < 20 | 1 | 3 | 3 | 3 | 8 | 4 | 1 | 1 | 0.2 | 1 | 1 | 3 | 3 | 2 | 7 | 3 | 2 | 3 | 9 | 6 | 4 | 9 | 13 | 5 | 3 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| | | | | Low | <25th Percentile | < 32 | 9 | 4 | 4 | 4 | 7 | 4 | 2 | 2 | 1 | 2 | 2 | 3 | 4 | 3 | 6 | 4 | 3 | 4 | 7 | 5 | 4 | 7 | 9 | 5 | 4 |
| | | | | Moderate | 25th-75th Percentile | 32-66 | 36 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 66 | 40 | 5 | 5 | 5 | 4 | 4 | 5 | 5 | 7 | 7 | 6 | 5 | 4 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 6 | 5 | 6 |
| | | | | Very High | >95th Percentile | > 124 | 13 | 5 | 5 | 5 | 5 | 4 | 6 | 6 | 7 | 8 | 6 | 5 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 4 | 7 | 5 | 7 |
| Site 24 | Central | General site | 2012 | Very Low | <5th Percentile | < 10 | 1 | 2 | 0.3 | 4 | 5 | 4 | 2 | 1 | 5 | 9 | 14 | 15 | 8 | 4 | 5 | 5 | 5 | 2 | 1 | 1 | 1 | 1 | 3 | 1 | 2 |
| | | | | Low | <25th Percentile | < 23 | 7 | 3 | 3 | 4 | 5 | 4 | 3 | 2 | 4 | 7 | 9 | 9 | 7 | 4 | 5 | 6 | 6 | 4 | 2 | 2 | 2 | 3 | 3 | 2 | 3 |
| | | | | Moderate | 25th-75th Percentile | 23-56 | 38 | 4 | 5 | 4 | 4 | 4 | 5 | 5 | 4 | 3 | 3 | 3 | 4 | 5 | 4 | 4 | 4 | 5 | 5 | 4 | 5 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 56 | 42 | 6 | 5 | 5 | 5 | 4 | 4 | 5 | 4 | 3 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 4 | 9 | 8 | 5 | 5 | 6 | 7 |
| | | | | Very High | >95th Percentile | > 99 | 13 | 7 | 5 | 5 | 6 | 3 | 4 | 5 | 3 | 3 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 4 | 9 | 9 | 5 | 5 | 7 | 8 |
| | | | 2013 | Very Low | <5th Percentile | < 11 | 1 | 5 | 4 | 7 | 4 | 3 | 2 | 2 | 9 | 10 | 9 | 4 | 1 | 2 | 3 | 3 | 4 | 2 | 1 | 2 | 1 | 5 | 6 | 4 | 5 |
| | | | | Low | <25th Percentile | < 22 | 8 | 5 | 4 | 6 | 4 | 4 | 3 | 2 | 6 | 8 | 7 | 4 | 2 | 2 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 5 | 6 | 4 | 5 |
| | | | | Moderate | 25th-75th Percentile | 22-51 | 36 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 3 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 51 | 42 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 2 | 1 | 1 | 2 | 4 | 3 | 3 | 5 | 5 | 8 | 7 | 6 |
| | | | | Very High | >95th Percentile | > 96 | 13 | 5 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 4 | 4 | 3 | 2 | 0.1 | 0.3 | 1 | 3 | 2 | 2 | 5 | 5 | 11 | 9 | 7 |
| | | | 2014 | Very Low | <5th Percentile | < 12 | 1 | 10 | 8 | 6 | 4 | 3 | 0.4 | 1 | 6 | 6 | 6 | 5 | 2 | 2 | 4 | 2 | 1 | 1 | 1 | 7 | 7 | 4 | 4 | 4 | 6 |
| | | | | Low | <25th Percentile | < 23 | 8 | 7 | 7 | 5 | 4 | 4 | 3 | 2 | 5 | 5 | 5 | 5 | 3 | 3 | 5 | 2 | 2 | 2 | 2 | 5 | 6 | 5 | 4 | 4 | 5 |
| | | | | Moderate | 25th-75th Percentile | 23-49 | 36 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 49 | 42 | 5 | 5 | 4 | 5 | 5 | 4 | 5 | 6 | 5 | 4 | 3 | 3 | 2 | 1 | 2 | 3 | 4 | 4 | 4 | 4 | 6 | 6 | 6 | 5 |
| | | | | Very High | >95th Percentile | > 94 | 14 | 5 | 5 | 4 | 6 | 5 | 4 | 5 | 7 | 5 | 4 | 3 | 3 | 1 | 0.4 | 1 | 2 | 3 | 4 | 3 | 4 | 6 | 6 | 6 | 6 |
| | | | 2015 | Very Low | <5th Percentile | < 10 | 1 | 9 | 8 | 4 | 6 | 6 | 4 | 3 | 13 | 7 | 5 | 5 | 0.4 | 1 | 1 | 0.4 | 1 | 1 | 2 | 3 | 2 | 3 | 3 | 6 | 6 |
| | | | | Low | <25th Percentile | < 20 | 7 | 7 | 6 | 5 | 5 | 6 | 4 | 3 | 9 | 6 | 5 | 5 | 1 | 2 | 2 | 1 | 2 | 3 | 3 | 4 | 4 | 4 | 4 | 6 | 6 |
| | | | | Moderate | 25th-75th Percentile | 20-45 | 38 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 45 | 42 | 6 | 5 | 4 | 4 | 6 | 5 | 6 | 6 | 4 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 1 | 2 | 4 | 5 | 7 | 7 | 6 | 6 |
| | | | | Very High | >95th Percentile | > 79 | 12 | 7 | 5 | 4 | 4 | 7 | 5 | 7 | 7 | 4 | 3 | 2 | 1 | 0.3 | 1 | 2 | 2 | 1 | 1 | 3 | 4 | 8 | 9 | 7 | 6 |
| Site 25 | Central | General site | 2012 | Very Low | <5th Percentile | < 15 | 1 | 5 | 6 | 10 | 13 | 8 | 9 | 1 | 0.4 | 4 | 0.2 | 1 | 2 | 3 | 3 | 4 | 4 | 9 | 2 | 1 | 0.5 | 1 | 5 | 5 | 6 |
| | | | | Low | <25th Percentile | < 27 | 8 | 5 | 6 | 8 | 10 | 7 | 6 | 1 | 1 | 3 | 1 | 2 | 3 | 4 | 4 | 4 | 5 | 7 | 3 | 2 | 2 | 2 | 4 | 5 | 6 |
| | | | | Moderate | 25th-75th Percentile | 27-63 | 37 | 4 | 3 | 3 | 3 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 5 | 4 | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 63 | 42 | 4 | 4 | 3 | 3 | 3 | 4 | 9 | 12 | 11 | 5 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 3 | 7 | 6 | 6 | 4 |
| | | | | Very High | >95th Percentile | > 110 | 12 | 4 | 4 | 3 | 3 | 3 | 4 | 11 | 16 | 13 | 4 | 2 | 1 | 1 | 1 | 1 | 1 | 0.1 | 1 | 1 | 2 | 8 | 7 | 7 | 4 |
| | | | 2013 | Very Low | <5th Percentile | < 22 | 1 | 9 | 9 | 8 | 12 | 6 | 2 | 1 | 1 | 0.3 | 0.3 | 1 | 2 | 2 | 2 | 12 | 7 | 3 | 2 | 2 | 1 | 7 | 2 | 3 | 6 |
| | | | | Low | <25th Percentile | < 39 | 9 | 8 | 8 | 7 | 9 | 6 | 3 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 3 | 8 | 6 | 4 | 3 | 2 | 2 | 6 | 3 | 4 | 6 |
| | | | | Moderate | 25th-75th Percentile | 39-81 | 38 | 3 | 3 | 3 | 3 | 4 | 4 | 5 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75th Percentile | > 81 | 39 | 4 | 4 | 3 | 3 | 3 | 4 | 8 | 9 | 8 | 5 | 3 | 3 | 2 | 1 | 2 | 1 | 1 | 2 | 3 | 5 | 5 | 7 | 7 | 5 |
| | | | | Very High | >95th Percentile | > 137 | 12 | 5 | 5 | 3 | 3 | 4 | 5 | 8 | 10 | 9 | 5 | 2 | 2 | 1 | 0.4 | 1 | 0.2 | 0.4 | 1 | 1 | 5 | 6 | 8 | 8 | 6 |
| Site 26 | Central | General site | 2013 | Very Low | <5th Percentile | < 8 | 0.4 | 4 | 11 | 12 | 12 | 5 | 4 | 1 | 1 | 0.3 | 2 | 3 | 6 | 6 | 8 | 8 | 6 | 4 | 2 | 1 | 1 | 1 | 1 | 1 | 2 |
| | | | | Low | <25th Percentile | < 20 | 6 | 5 | 7 | 8 | 8 | 6 | 4 | 2 | 1 | 1 | 3 | 4 | 5 | 6 | 6 | 7 | 5 | 4 | 3 | 2 | 2 | 1 | 2 | 2 | 4 |
| | | | | Moderate | 25th-75th Percentile | 20-56 | 34 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 |
| | | | | High | >75th Percentile | > 56 | 45 | 5 | 4 | 2 | 2 | 3 | 3 | 6 | 9 | 6 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 5 | 7 | 9 | 8 | 7 | 6 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| | | | | Very High | >95$^{th}$ Percentile | > 110 | 14 | 5 | 5 | 2 | 1 | 2 | 3 | 7 | 10 | 5 | 3 | 2 | 1 | 0.3 | 0.1 | 0.1 | 1 | 1 | 1 | 4 | 8 | 11 | 10 | 9 | 8 |
| | | | 2014 | Very Low | <5$^{th}$ Percentile | < 9 | 0.5 | 12 | 13 | 11 | 7 | 5 | 1 | 0.4 | 1 | 2 | 3 | 3 | 4 | 5 | 7 | 5 | 3 | 1 | 0.3 | - | 0.4 | 1 | 2 | 4 | 9 |
| | | | | Low | <25$^{th}$ Percentile | < 23 | 6 | 8 | 9 | 8 | 6 | 5 | 3 | 1 | 1 | 2 | 3 | 4 | 5 | 7 | 7 | 5 | 4 | 3 | 2 | 1 | 2 | 2 | 3 | 4 | 6 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 23-57 | 35 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | > 57 | 44 | 3 | 3 | 3 | 3 | 3 | 5 | 7 | 10 | 5 | 3 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 4 | 7 | 9 | 9 | 8 | 5 | 3 |
| | | | | Very High | >95$^{th}$ Percentile | > 109 | 14 | 3 | 2 | 2 | 3 | 3 | 5 | 7 | 11 | 6 | 3 | 1 | 0.3 | 1 | 0.4 | 1 | 1 | 1 | 3 | 7 | 11 | 11 | 9 | 6 | 3 |
| Site 27 | Central | | 2014 | Very Low | <5$^{th}$ Percentile | < 13 | 0.5 | 5 | 3 | 4 | 5 | 4 | 4 | 4 | 3 | 1 | 4 | 4 | 5 | 7 | 6 | 7 | 8 | 7 | 3 | 2 | 2 | 2 | 2 | 2 | 4 |
| | | | | Low | <25$^{th}$ Percentile | < 33 | 8 | 5 | 5 | 6 | 5 | 5 | 4 | 4 | 2 | 2 | 3 | 4 | 6 | 6 | 6 | 7 | 6 | 5 | 4 | 3 | 2 | 2 | 2 | 3 | 4 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 33-73 | 39 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | > 73 | 41 | 6 | 4 | 4 | 3 | 4 | 4 | 4 | 6 | 8 | 6 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 6 | 8 | 9 | 7 | 7 |
| | | | | Very High | >95$^{th}$ Percentile | > 127 | 13 | 6 | 4 | 4 | 3 | 4 | 4 | 4 | 6 | 7 | 6 | 4 | 1 | 1 | 1 | 1 | 0.1 | 1 | 1 | 2 | 6 | 8 | 10 | 9 | 7 |
| Site 28 | Central | General site | 2014 | Very Low | <5$^{th}$ Percentile | < 9 | 0.4 | 6 | 6 | 5 | 3 | 2 | 2 | 1 | 0.2 | - | 1 | 5 | 6 | 6 | 5 | 9 | 11 | 9 | 5 | 2 | 1 | 3 | 2 | 4 | 5 |
| | | | | Low | <25$^{th}$ Percentile | < 21 | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 2 | 1 | 1 | 2 | 4 | 5 | 6 | 6 | 7 | 8 | 7 | 5 | 5 | 4 | 4 | 4 | 4 | 5 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 21-66 | 31 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | > 66 | 47 | 5 | 5 | 4 | 4 | 4 | 6 | 6 | 7 | 8 | 6 | 3 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 6 | 7 | 8 | 6 |
| | | | | Very High | >95$^{th}$ Percentile | > 146 | 16 | 5 | 5 | 4 | 4 | 4 | 7 | 7 | 7 | 9 | 7 | 3 | 2 | 1 | 1 | 1 | 0.5 | 0.3 | 0.4 | 0.2 | 2 | 7 | 9 | 10 | 7 |
| Site 47 | Central | General site | 2015 | Very Low | <5$^{th}$ Percentile | < 8 | 0.4 | 5 | 6 | 5 | 4 | 3 | 1 | 2 | 1 | 0.2 | 1 | 4 | 4 | 7 | 10 | 8 | 6 | 8 | 6 | 5 | 4 | 2 | 2 | 2 | 3 |
| | | | | Low | <25$^{th}$ Percentile | < 19 | 6 | 4 | 5 | 4 | 4 | 4 | 4 | 3 | 2 | 1 | 3 | 4 | 4 | 6 | 7 | 7 | 6 | 6 | 5 | 5 | 4 | 3 | 3 | 3 | 3 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 19-57 | 37 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | > 57 | 44 | 5 | 4 | 5 | 5 | 5 | 4 | 3 | 4 | 7 | 7 | 4 | 3 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 4 | 6 | 8 | 8 | 6 |
| | | | | Very High | >95$^{th}$ Percentile | > 105 | 13 | 6 | 4 | 5 | 6 | 6 | 4 | 3 | 4 | 8 | 9 | 4 | 3 | 1 | 0.4 | 0.1 | 0.2 | - | 1 | 1 | 3 | 7 | 9 | 9 | 6 |
| Site 49 | Central | General site | 2011 | Very Low | <5$^{th}$ Percentile | < 21 | 1 | 10 | 8 | 10 | 7 | 4 | 4 | 0.2 | 0.1 | 1 | 3 | 4 | 9 | 7 | 6 | 5 | 3 | 3 | 1 | 0.5 | 1 | 1 | 1 | 4 | 8 |
| | | | | Low | <25$^{th}$ Percentile | < 47 | 7 | 7 | 6 | 7 | 6 | 4 | 3 | 1 | 1 | 2 | 4 | 6 | 8 | 8 | 7 | 6 | 5 | 3 | 2 | 1 | 1 | 2 | 2 | 4 | 6 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 47-124 | 37 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 3 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | > 124 | 42 | 4 | 3 | 2 | 2 | 2 | 3 | 9 | 9 | 4 | 2 | 1 | 0.4 | 0.3 | 0.4 | 1 | 1 | 1 | 3 | 6 | 9 | 12 | 11 | 7 | 6 |
| | | | | Very High | >95$^{th}$ Percentile | > 218 | 13 | 5 | 4 | 2 | 1 | 2 | 2 | 10 | 10 | 4 | 1 | 0.1 | - | 0.1 | 0.1 | 0.5 | 0.4 | 0.3 | 2 | 5 | 9 | 14 | 13 | 8 | 7 |
| | | | 2012 | Very Low | <5$^{th}$ Percentile | < 22 | 1 | 6 | 13 | 6 | 2 | 2 | 1 | 0.2 | 0.3 | 5 | 6 | 6 | 7 | 7 | 10 | 4 | 2 | 2 | 1 | 1 | 0.5 | 2 | 6 | 3 | 8 |
| | | | | Low | <25$^{th}$ Percentile | < 48 | 6 | 5 | 8 | 5 | 3 | 2 | 1 | 1 | 1 | 4 | 7 | 7 | 7 | 8 | 8 | 6 | 5 | 3 | 1 | 1 | 1 | 2 | 4 | 3 | 5 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 48-145 | 36 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | > 145 | 45 | 4 | 3 | 3 | 3 | 3 | 4 | 8 | 11 | 5 | 1 | 1 | 0.2 | 0.2 | 0.2 | 0.4 | 1 | 1 | 3 | 6 | 9 | 9 | 9 | 8 | 5 |
| | | | | Very High | >95$^{th}$ Percentile | > 268 | 13 | 4 | 3 | 3 | 2 | 1 | 2 | 8 | 15 | 5 | 1 | 0.1 | - | - | - | - | - | 0.3 | 2 | 6 | 10 | 11 | 12 | 10 | 5 |
| | | | 2014 | Very Low | <5$^{th}$ Percentile | < 19 | 1 | 5 | 8 | 8 | 3 | 2 | 1 | - | 0.2 | 1 | 4 | 8 | 6 | 12 | 7 | 7 | 9 | 3 | 1 | 2 | 1 | 1 | 2 | 4 | 5 |
| | | | | Low | <25$^{th}$ Percentile | < 44 | 6 | 5 | 6 | 6 | 5 | 3 | 2 | 1 | 1 | 2 | 5 | 7 | 6 | 9 | 7 | 7 | 7 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 4 |
| | | | | Moderate | 25$^{th}$-75$^{th}$ Percentile | 44-124 | 36 | 4 | 4 | 5 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >75$^{th}$ Percentile | > 124 | 43 | 5 | 2 | 2 | 2 | 3 | 4 | 10 | 11 | 5 | 2 | 1 | 0.5 | 0.2 | 0.2 | 1 | 1 | 2 | 4 | 6 | 8 | 8 | 8 | 7 | 6 |
| | | | | Very High | >95$^{th}$ Percentile | > 234 | 14 | 6 | 2 | 2 | 2 | 2 | 3 | 10 | 13 | 5 | 1 | 1 | 0.1 | - | 0.1 | 0.1 | 1 | 2 | 4 | 6 | 8 | 8 | 9 | 9 | 7 |
| | | | 2015 | Very Low | <5$^{th}$ Percentile | < 23 | 1 | 8 | 9 | 7 | 5 | 5 | 3 | 0.5 | 1 | 3 | 4 | 4 | 6 | 6 | 4 | 5 | 4 | 1 | 0.1 | 0.4 | 1 | 3 | 4 | 5 | 12 |
| | | | | Low | <25$^{th}$ Percentile | < 45 | 7 | 6 | 7 | 6 | 5 | 4 | 3 | 1 | 1 | 4 | 5 | 5 | 6 | 6 | 5 | 6 | 5 | 3 | 2 | 1 | 1 | 3 | 3 | 4 | 8 |

| Site | Region | Category | Year | Contribution of hourly $PM_{10}$ concentrations to annual average $PM_{10}$ | | | Contribution of hourly $PM_{10}$ concentrations at different percentiles to annual average $PM_{10}$ (%) | Hourly Contribution (%) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Concentration Level | Percentile | Concentration ($\mu g\ m^{-3}$) | | H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 | H22 | H23 |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 45-124 | 34 | 4 | 4 | 4 | 4 | 4 | 5 | 3 | 4 | 4 | 4 | 4 | 5 | 4 | 5 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | | | High | >$75^{th}$ Percentile | > 124 | 45 | 4 | 2 | 2 | 2 | 4 | 6 | 11 | 11 | 5 | 2 | 1 | 0.4 | 0.2 | 0.5 | 1 | 2 | 2 | 4 | 7 | 9 | 9 | 7 | 5 | 5 |
| | | | | Very High | >$95^{th}$ Percentile | > 256 | 14 | 4 | 2 | 1 | 1 | 3 | 6 | 13 | 15 | 5 | 1 | - | 0.2 | 0.2 | 0.3 | 0.2 | 1 | 1 | 2 | 6 | 10 | 10 | 8 | 5 | 5 |
| Site 51 | Central | | 2014 | Very Low | <$5^{th}$ Percentile | < 14 | 1 | 8 | 8 | 7 | 10 | 12 | 6 | 3 | 1 | 1 | 1 | 2 | 4 | 4 | 4 | 3 | 1 | 2 | 2 | 3 | 1 | 4 | 2 | 4 | 4 |
| | | | | Low | <$25^{th}$ Percentile | < 28 | 7 | 6 | 7 | 7 | 8 | 9 | 6 | 4 | 2 | 2 | 3 | 4 | 4 | 5 | 4 | 4 | 3 | 3 | 2 | 2 | 1 | 3 | 3 | 4 | 5 |
| | | | | Moderate | $25^{th}$-$75^{th}$ Percentile | 28-72 | 37 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 5 | 4 | 5 | 5 | 5 | 5 | 4 | 3 | 4 | 4 | 4 |
| | | | | High | >$75^{th}$ Percentile | > 72 | 42 | 5 | 5 | 4 | 3 | 3 | 3 | 3 | 5 | 7 | 6 | 5 | 3 | 2 | 2 | 1 | 1 | 1 | 2 | 3 | 6 | 9 | 9 | 8 | 6 |
| | | | | Very High | >$95^{th}$ Percentile | > 131 | 13 | 6 | 5 | 4 | 3 | 4 | 2 | 4 | 5 | 8 | 7 | 6 | 2 | 1 | 1 | 0.5 | 1 | 0.4 | 0.5 | 1 | 6 | 10 | 10 | 9 | 6 |

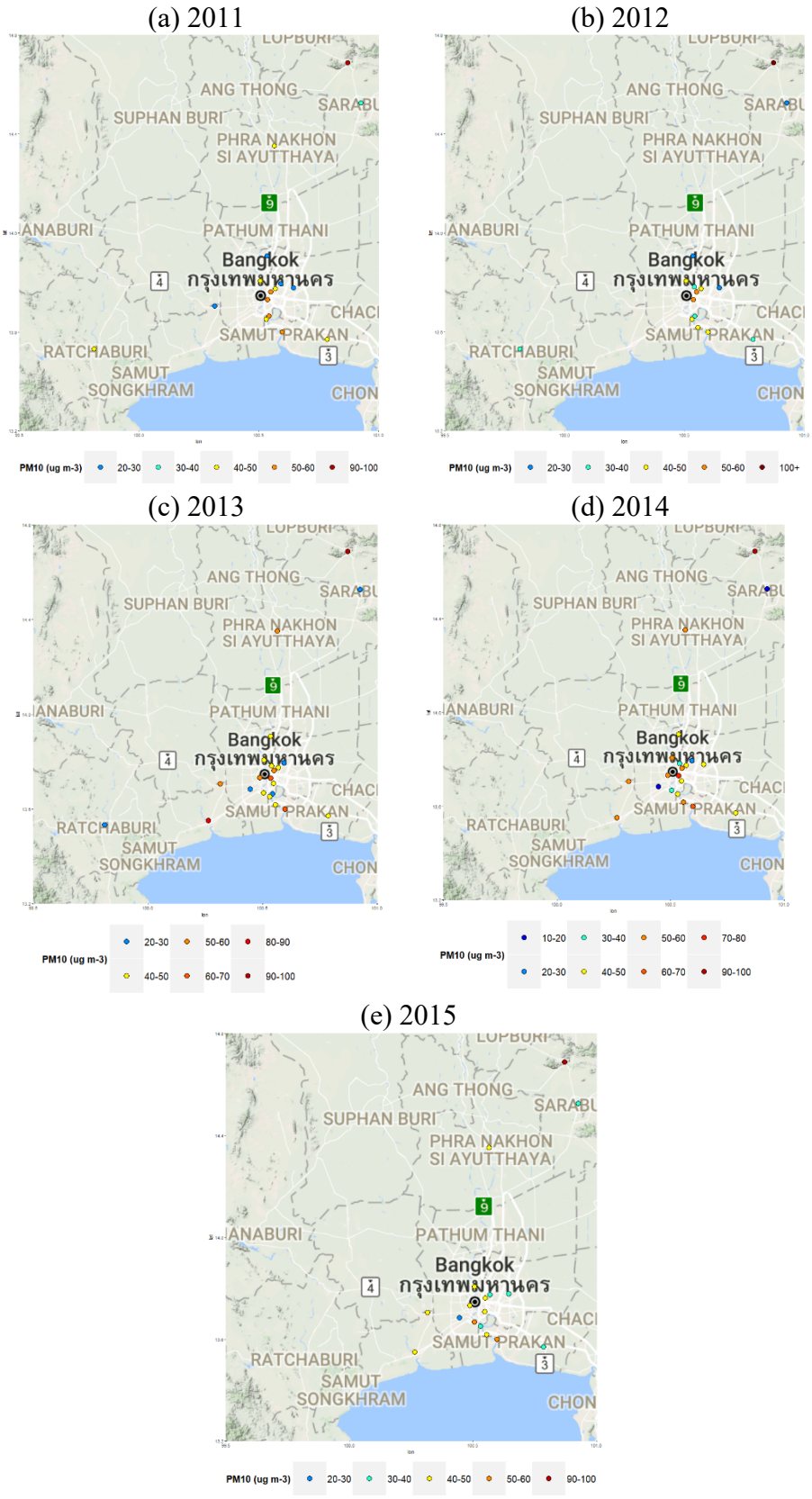
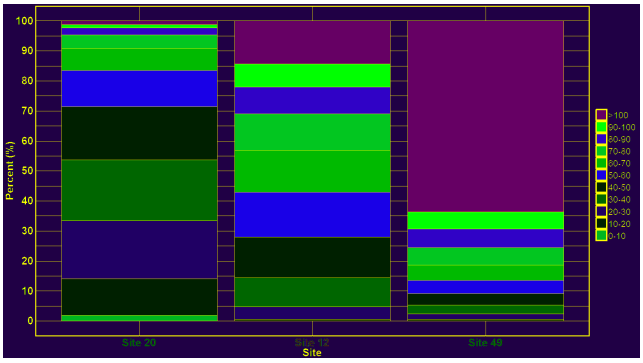
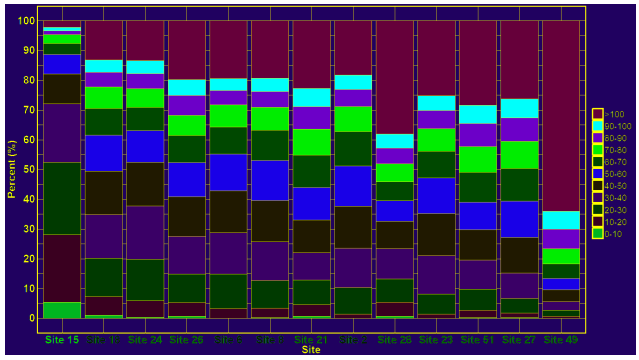


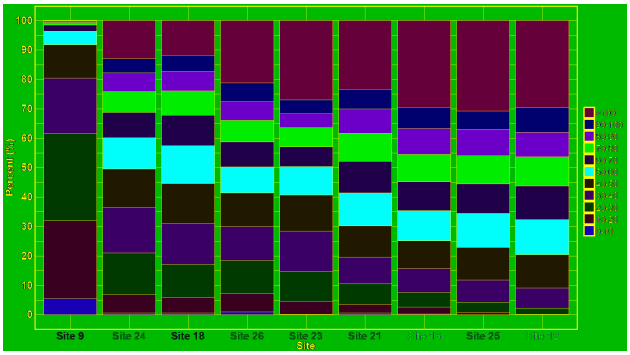

**Figure S1:** Annual average $PM_{10}$ concentrations for an individual year in central Thailand between 2011 and 2015



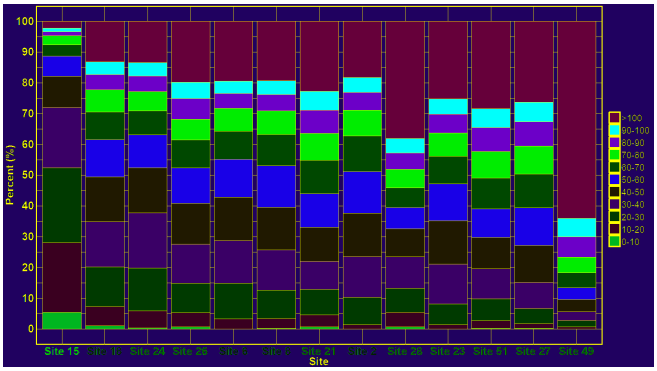

(a) 2011



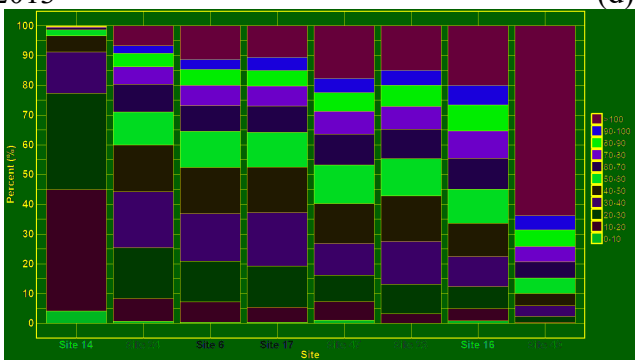

(b) 2012




(c) 2013

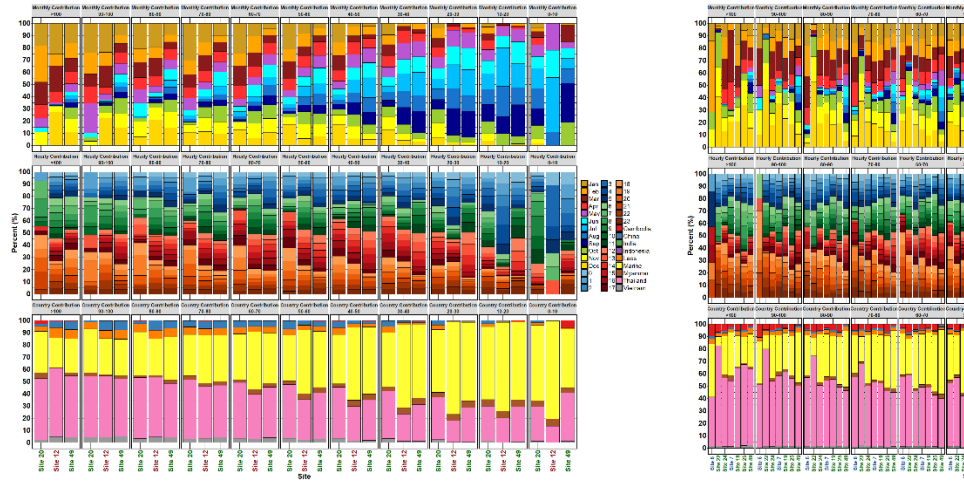



(d) 2014

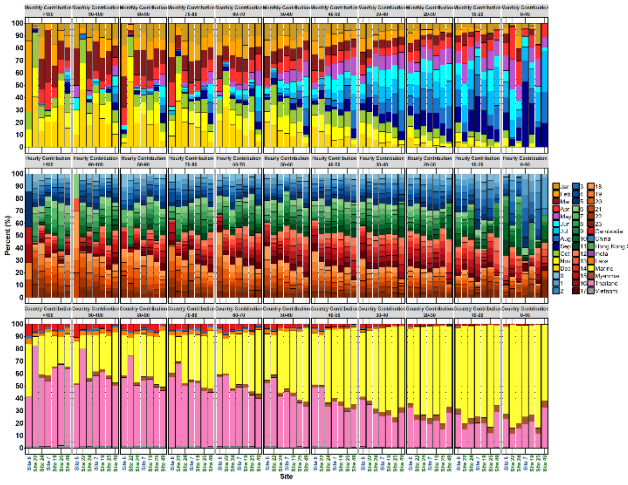



(e) 2015

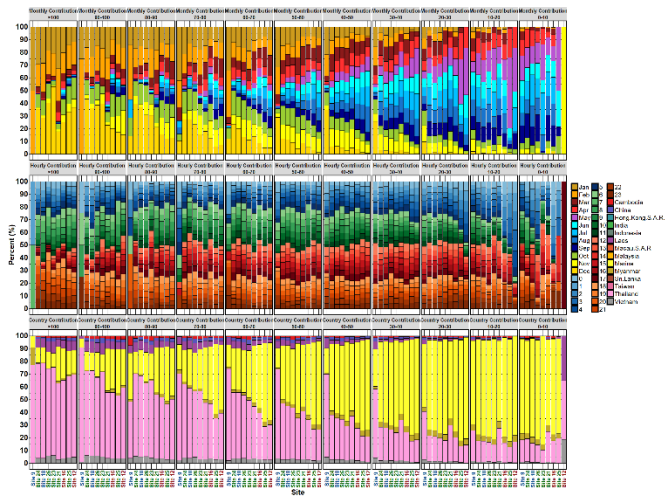
**Figure S2:** Summary of hourly $PM_{10}$ concentrations contribution to annual average for an individual year across central Thailand between 2011 and 2015



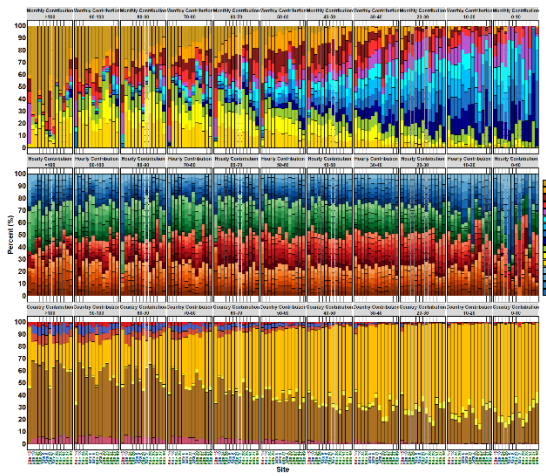
(a) 2011



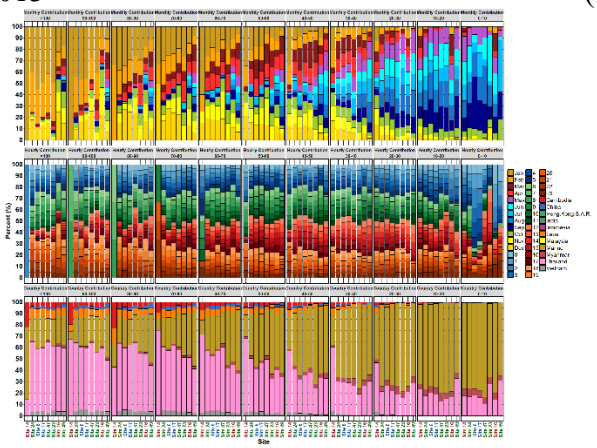
(b) 2012



(c) 2013



(d) 2014



(e) 2015

**Figure S3:** Summary of hourly $PM_{10}$ concentrations contribution to annual average for an individual year across central Thailand from monthly, hourly and country contribution between 2011 and 2015

# Chapter 5

**Table S16:** Historical emissions of $PM_{2.5}$ between 2010-2017 from different source sectors across Thailand

| Sectors | PM2.5 (kt) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | Average 2010-2017 |
| Agriculture | 62.3 | 68.1 | 68.1 | 66.4 | 59.2 | 53.0 | 58.4 | 58.9 | 61.8 |
| Agriculture Forestry and Fishing | 13.8 | 14.5 | 14.9 | 15.4 | 15.7 | 15.5 | 11.8 | 10.6 | 14.0 |
| Charcoal Making | 64.9 | 59.4 | 48.1 | 62.3 | 59.0 | 58.5 | 42.2 | 36.3 | 53.8 |
| Coke Production | 7.0 | 4.3 | 5.3 | 1.0 | 4.8 | 4.3 | 1.7 | 1.5 | 3.7 |
| Electricity Generation | 13.2 | 15.5 | 14.1 | 20.4 | 23.1 | 23.5 | 53.7 | 47.4 | 26.4 |
| Energy Industry Own Use | 0.2 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 | 0.2 | 0.3 |
| Industry | 79.7 | 69.4 | 77.4 | 73.1 | 72.5 | 67.2 | 67.7 | 67.1 | 71.8 |
| Residential | 68.5 | 68.3 | 51.1 | 66.3 | 64.1 | 68.9 | 71.1 | 73.3 | 66.5 |
| Transport | 56.3 | 53.0 | 50.1 | 47.6 | 45.3 | 43.4 | 41.7 | 40.2 | 47.2 |
| Vegetation Fires | 93.3 | 26.0 | 104.4 | 62.6 | 136.9 | 109.2 | 144.4 | 144.4 | 102.6 |
| Waste | 85.6 | 91.8 | 80.1 | 83.1 | 79.3 | 79.8 | 68.7 | 42.3 | 76.3 |
| **Total** | **544.7** | **470.7** | **514.1** | **498.7** | **560.4** | **523.6** | **561.7** | **522.3** | **524.5** |

**Table S17:** Historical emissions of BC between 2010-2017 from different source sectors across Thailand

| Sectors | BC (kt) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | Average 2010-2017 |
| Agriculture | 5.7 | 6.3 | 6.3 | 6.1 | 5.5 | 4.9 | 5.4 | 5.4 | 5.7 |
| Agriculture Forestry and Fishing | 5.7 | 6.1 | 6.2 | 6.4 | 6.5 | 6.4 | 4.9 | 4.4 | 5.8 |
| Charcoal Making | 4.7 | 4.3 | 3.5 | 4.6 | 4.3 | 4.3 | 3.1 | 2.7 | 3.9 |
| Coke Production | 1.3 | 0.8 | 1.0 | 0.2 | 0.9 | 0.8 | 0.3 | 0.3 | 0.7 |
| Electricity Generation | 0.3 | 0.4 | 0.4 | 0.6 | 0.7 | 0.7 | 1.7 | 1.5 | 0.8 |
| Industry | 14.7 | 13.4 | 15.9 | 15.6 | 17.0 | 15.7 | 15.1 | 14.6 | 15.3 |
| Residential | 12.8 | 12.5 | 9.5 | 12.4 | 11.9 | 12.5 | 12.4 | 12.3 | 12.0 |
| Transport | 30.7 | 29.6 | 28.5 | 27.7 | 27.0 | 26.4 | 25.9 | 25.5 | 27.7 |
| Vegetation Fires | 6.8 | 1.9 | 7.6 | 4.6 | 9.9 | 7.9 | 10.5 | 10.5 | 7.5 |
| Waste | 5.7 | 6.1 | 5.3 | 5.5 | 5.3 | 5.3 | 4.6 | 2.8 | 5.1 |
| **Total** | **88.6** | **81.5** | **84.4** | **83.8** | **89.0** | **84.9** | **83.9** | **79.9** | **84.5** |

**Table S18:** Historical emissions of OC between 2010-2017 from different source sectors across Thailand

| Sectors | OC (kt) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | Average 2010-2017 |
| Agriculture | 37.4 | 40.9 | 40.9 | 39.9 | 35.5 | 31.8 | 35.0 | 35.4 | 37.1 |
| Agriculture Forestry and Fishing | 4.0 | 4.2 | 4.3 | 4.5 | 4.6 | 4.5 | 3.4 | 3.1 | 4.1 |
| Charcoal Making | 32.2 | 29.5 | 23.9 | 30.9 | 29.3 | 29.0 | 20.9 | 18.0 | 26.7 |
| Coke Production | 1.0 | 0.6 | 0.7 | 0.1 | 0.6 | 0.6 | 0.2 | 0.2 | 0.5 |
| Electricity Generation | 1.3 | 1.7 | 1.6 | 2.3 | 2.6 | 2.6 | 6.8 | 5.8 | 3.1 |
| Energy Industry Own Use | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Industry | 31.1 | 27.9 | 31.6 | 29.8 | 30.9 | 28.3 | 26.0 | 27.2 | 29.1 |
| Residential | 28.9 | 28.9 | 21.5 | 27.9 | 27.0 | 29.1 | 32.2 | 33.3 | 28.6 |
| Transport | 14.6 | 13.4 | 12.3 | 11.3 | 10.4 | 9.6 | 8.9 | 8.3 | 11.1 |
| Vegetation Fires | 51.1 | 13.9 | 57.3 | 34.4 | 76.0 | 60.4 | 80.9 | 80.9 | 56.9 |
| Waste | 46.0 | 49.4 | 43.1 | 44.7 | 42.7 | 42.9 | 36.9 | 22.7 | 41.0 |
| **Total** | **247.6** | **210.5** | **237.5** | **226.1** | **259.9** | **239.1** | **251.6** | **235.0** | **238.4** |

**Table S19:** Historical emissions of $NH_3$ between 2010-2017 from different source sectors across Thailand

| Sectors | $NH_3$ (kt) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | Average 2010-2017 |
| Agriculture | 570.4 | 562.8 | 591.7 | 585.2 | 568.1 | 560.7 | 567.6 | 586.0 | 574.1 |
| Charcoal Making | 9.2 | 8.5 | 6.9 | 8.9 | 8.4 | 8.3 | 6.0 | 5.2 | 7.7 |
| Commercial and Public Services | 0.1 | 0.1 | 0.1 | 0.1 | - | - | - | - | 0.1 |
| Electricity Generation | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Energy Industry Own Use | 0.4 | 0.4 | 0.5 | 0.6 | 0.6 | 0.6 | 0.5 | 0.3 | 0.5 |
| Industry | 0.3 | 47.9 | 50.4 | 49.1 | 72.2 | 49.2 | 58.9 | 63.0 | 48.9 |
| Residential | 12.1 | 11.9 | 9.0 | 11.7 | 11.2 | 11.8 | 13.0 | 13.1 | 11.8 |
| Transport | 4.3 | 4.5 | 5.0 | 5.5 | 5.6 | 6.0 | 6.3 | 6.6 | 5.5 |
| Vegetation Fires | 11.9 | 3.1 | 13.4 | 8.1 | 18.1 | 14.3 | 19.6 | 19.6 | 13.5 |
| Waste | 9.8 | 10.5 | 9.2 | 9.5 | 9.1 | 9.1 | 7.9 | 4.8 | 8.7 |
| **Total** | **618.5** | **649.8** | **686.3** | **678.8** | **693.5** | **660.2** | **679.9** | **698.8** | **670.7** |

**Table S20:** Historical emissions of $NO_x$ between 2010-2017 from different source sectors across Thailand

| Sectors | NOx (kt) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **Average 2010-2017** |
| Agriculture | 92.6 | 93.4 | 98.1 | 101.9 | 103.4 | 105.4 | 107.7 | 107.9 | 101.3 |
| Agriculture Forestry and Fishing | 135.4 | 142.9 | 146.7 | 151.5 | 153.9 | 151.7 | 115.8 | 103.6 | 137.7 |
| Charcoal Making | 4.5 | 4.1 | 3.3 | 4.3 | 4.1 | 4.0 | 2.9 | 2.5 | 3.7 |
| Commercial and Public Services | 3.7 | 3.4 | 3.6 | 2.8 | 1.3 | 1.9 | 1.9 | 2.4 | 2.6 |
| Electricity Generation | 157.1 | 171.1 | 162.1 | 166.2 | 175.9 | 169.3 | 198.9 | 195.9 | 174.6 |
| Energy Industry Own Use | 16.5 | 18.9 | 23.4 | 28.3 | 28.0 | 25.2 | 21.7 | 15.7 | 22.2 |
| Industry | 136.3 | 128.1 | 155.4 | 176.0 | 193.1 | 184.9 | 204.1 | 175.1 | 169.1 |
| Oil Refining | 2.3 | 2.4 | 2.5 | 2.6 | 2.8 | 2.8 | 2.9 | 2.8 | 2.6 |
| Residential | 30.1 | 29.3 | 23.2 | 29.3 | 28.5 | 29.8 | 23.1 | 22.7 | 27.0 |
| Transport | 643.5 | 631.8 | 622.9 | 622.1 | 616.2 | 618.6 | 621.6 | 624.9 | 625.2 |
| Vegetation Fires | 37.1 | 12.9 | 39.7 | 24.1 | 48.3 | 39.7 | 47.4 | 47.4 | 37.1 |
| Waste | 45.7 | 49.0 | 44.3 | 44.5 | 42.1 | 43.0 | 37.5 | 50.5 | 44.6 |
| **Total** | **1,304.8** | **1,287.4** | **1,325.3** | **1,353.7** | **1,397.7** | **1,376.4** | **1,385.5** | **1,351.4** | **1,347.8** |

**Table S21:** Historical emissions of $SO_2$ between 2010-2017 from different source sectors across Thailand

| Sectors | SO2 (kt) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **Average 2010-2017** |
| Agriculture | 3.6 | 4.0 | 4.0 | 3.9 | 3.6 | 3.2 | 3.5 | 3.5 | 3.7 |
| Agriculture Forestry and Fishing | 66.3 | 69.9 | 71.8 | 74.1 | 75.7 | 74.2 | 56.5 | 50.7 | 67.4 |
| Charcoal Making | 14.4 | 13.2 | 10.7 | 13.8 | 13.1 | 12.9 | 9.3 | 8.0 | 11.9 |
| Commercial and Public Services | 0.1 | 0.1 | 0.1 | - | 0.1 | - | - | - | 0.1 |
| Electricity Generation | 353.3 | 384.1 | 362.7 | 393.2 | 394.7 | 357.4 | 381.9 | 394.3 | 377.7 |
| Industry | 386.9 | 365.2 | 363.3 | 371.2 | 342.9 | 298.3 | 316.5 | 301.1 | 343.2 |
| Oil Refining | 35.2 | 36.2 | 38.4 | 39.9 | 42.9 | 43.4 | 44.2 | 42.4 | 40.3 |
| Residential | 10.7 | 10.4 | 7.9 | 10.3 | 9.9 | 10.5 | 10.2 | 10.2 | 10.0 |
| Transport | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Vegetation Fires | 6.1 | 1.8 | 6.8 | 4.1 | 8.8 | 7.1 | 9.2 | 9.2 | 6.6 |
| Waste | 4.5 | 4.9 | 4.3 | 4.4 | 4.2 | 4.3 | 3.7 | 3.8 | 4.3 |
| **Total** | **881.1** | **889.8** | **870.0** | **915.1** | **896.0** | **811.5** | **835.2** | **823.4** | **865.3** |

# I. Energy sector

**Table S22:** Simple transport emission factors use in LEAP-IBC analysis

| Demand\Transport | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| **Domestic Aviation Simple\Aviation Gasoline** | | | | |
| Nitrogen Oxides NOx | 4 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors (Aviation Table 3-**3**)<br>c) Bond et al. (2004) value for aviation fuel, Table 7<br>d) Assume = factor for gasoline in road transport (simple method) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.14 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.14 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.1 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.03 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 1.44 ?d | Kilogramme | Metric Tonne | |
| **Domestic Aviation Simple\Gasoline Type Jetfuel** | | | | |
| Nitrogen Oxides NOx | 4 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors (Aviation Table 3-**3**)<br>c) Bond et al. (2004) value for aviation fuel, Table 7<br>d) Assume = factor for gasoline in road transport (simple method) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.14 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.14 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.1 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.03 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 1.44 ?d | Kilogramme | Metric Tonne | |
| **Domestic Aviation Simple\Kerosene Type Jetfuel** | | | | |
| Nitrogen Oxides NOx | 9.4 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2013) Tier 1 cruise emission factors for old fleet (Aviation Table 3-3)<br>c) Bond et al. (2004) value for aviation fuel, Table 7<br>d) Assume = factor for gasoline in road transport (simple method) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.14 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.14 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.1 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.03 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 1.44 ?d | Kilogramme | Metric Tonne | |
| **Road Transport Simple**<br>**Road Transport Simple\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 30 ?b | Kilogramme | Metric Tonne | |

| Demand\Transport | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factor (Tables 3-5 to 3-7: maximum values correspond to uncontrolled CNG Buses)<br>c) Assume BC is 5.4% of PM2.5 EMEP/EEA (2016) Tier 1 emission factor, small combustion (1.A.4 , Table 3-4)<br>d) Asume OC = 8.33xBC (Bond et al, 2004; Table 5) |
| Particulates $PM_{10}$ | 0.04 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.04 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.002 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.018 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.000 ?b | Kilogramme | Terajoule | |
| **Road Transport Simple\Motor Gasoline** | | | | |
| Nitrogen Oxides NOx | 29.89 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors (Tables 3-5 to 3-7: maximum values correspond to uncontrolled passenger cars)<br>c) BC and OC values are from Bond et al, 2004 (Tables 9 and 10 - from which central values are used for the technology/emission control mix for India in the mid 1990s (i.e. if a range is given by Bond et al., then upper value taken). The values assumes that 52% of gasoline vehicles are 'unimproved', 35% are 2-stroke (high emissions) and 13% are 'super-emitters'.) If 2-strokes and super-emitters are a small part of the gasoline-powered vehicle fleet, then use 0.14 (BC) and 0.15 (OC) for 'standards beginning' or 0.043 (BC) and 0.046 (OC) for 'standards in place' (Bond et al, 2004, Table 7) and re-calculate PM values using the formula in (d) below.<br>d) PM values calculated as BC+(1.3xOC). |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 7.5 ?d | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 7.5 ?d | Kilogramme | Metric Tonne | |
| Black Carbon | 0.43 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 5.4 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 1.44 ?b | Kilogramme | Metric Tonne | |
| **Road Transport Simple\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 38.29 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors, (Tables 3-5 to 3-7: maximum values correspond to uncontrolled HDVs)<br>c) From Bond et al. (2004; Table 5 and Table 9) from which central values are used for the technology/emission control mix for India in the mid 1990s (i.e. if a range is given by Bond et al., then upper value taken). PM values assumed to equal the total for BC + OM (ie. = BC+(1.3xOC)) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 5.0 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 5.0 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 3.6 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 1.1 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.018 ?b | Kilogramme | Metric Tonne | |
| **Road Transport Simple\LPG Liquefied Petroleum Gas** | | | | |
| Nitrogen Oxides NOx | 34.3 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factor for uncontrolled passenger cars<br>c) ARIA (2008) value for LPG cars in India<br>d) Assume BC is 5.4% of PM2.5 EMEP/EEA (2016) Tier 1 emission factor, small |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.035 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.035 ?c | Kilogramme | Metric Tonne | |

| Demand\Transport | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Black Carbon | 0.002 ?d | Kilogramme | Metric Tonne | combustion (1.A.4 , Table 3-4)<br>e) Assume OC = BC/1.3 (Bond et al, 2004; Table 5, ratio for residential LPG)) |
| Organic Carbon | 0.0015 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.108 ?b | Kilogramme | Metric Tonne | |
| **Road Transport Simple\Gas and Liquids from Biomass and Wastes** | | | | |
| Nitrogen Oxides NOx | 51 ?b | Kilogramme | Terajoule | **Note: We need emission factors for biogasoline (= ethanol?) and biodiesel here**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs: CO2 and N2O as for 'Other liquid biofuels' in residential use; CH4 as for ethanol cars in Brazil.<br>b) EMEP/EEA (2016) Tier 1 defaults for small combustion (Section 1.A.4, Table 3-5)<br>c) Emission factors needed |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.9 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 1.9 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.16 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0 ?c | Kilogramme | Terajoule | |
| Ammonia | 0 ?c | Kilogramme | Terajoule | |
| **Railways**<br>**Railways\Other Bituminous Coal and Anthracite** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for coal combustion in manufacturing industry (Section 1.A.2 Table 3-2)<br>c) Bond et al (2004): Hard coal factors for rail from Tables 9 and 10 |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.43 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 3.17 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 3 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.1 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.00028 ?b | Kilogramme | Metric Tonne | |
| **Railways\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 52.4 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.3.c Railways, Table 3-1)<br>c) Bond et al (2004) Table 7, diesel railroad.<br>d) Bond et al (2004): Diesel fuel factors for rail from Table 7 (BC-f = 0.65; OC = 0.21) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 2.7 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 2.7 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 1.53 ?d | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.49 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.007 ?b | Kilogramme | Metric Tonne | |

| Demand\Transport | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| **Domestic Shipping**<br>**Domestic Shipping\Motor Gasoline** | | | | |
| Nitrogen Oxides NOx | 9.4 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factor (Section 1.A.3, Table 3-3)<br>c) Bond et al (2004): Assuming BC/OC ratio as for gasoline/vehicles from Tables 9 and 10<br>d) EMEP/EEA (2013) Tier 1 emission factor for gasoline passenger cars |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 9.5 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 9.5 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.48 ?b | Kilogramme | Metric Tonne | |
| Organic Carbon | 5.97 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 1.44 ?d | Kilogramme | Metric Tonne | |
| **Domestic Shipping\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 78.5 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factor for marine diesel/marine gas oil (MDO/MGO) (Section 1.A.3, Table 3-2)<br>c) Assuming all PM2.5 is composed of BC and OC<br>d) EMEP/EEA (2013) Tier 1 emission factor for diesel HDV road transport |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.5 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 1.4 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.43 ?b | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.75 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.018 ?d | Kilogramme | Metric Tonne | |
| **Domestic Shipping\Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 79.3 ?b | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factor for bunker fuel oil used in ocean-going ships (as for international navigation). (Section 1.A.3, Table 3-1)<br>c) Bond et al (2004): Assuming BC/OC ratio as for heavy fuel oil/ships from Tables 9 and 10 |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 6.2 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 5.6 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.67 ?b | Kilogramme | Metric Tonne | |

| Demand\Transport | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Organic Carbon | 2.17 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.101 | Kilogramme | Metric Tonne | |
| **Pipelines**<br>**Pipelines\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2013) Tier 1 emission factor, non-residential, small combustion (1.A.4, Table 3-8)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Other or Non Specified Transport**<br>**Other or Non Specified Transport\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 30 ?b | Kilogramme | Metric Tonne | Assume all emission factors are as for Road Transport Simple<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factor (Tables 3-5 to 3-7: maximum values correspond to uncontrolled CNG Buses)<br>c) Assume BC is 5.4% of PM2.5 EMEP/EEA (2016) Tier 1 emission factor, small combustion (1.A.4 , Table 3-4)<br>d) Asume OC = 8.33xBC (Bond et al, 2004; Table 5) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.04 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.04 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.002 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.018 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.000 ?b | Kilogramme | Terajoule | |
| **Other or Non Specified Transport\Motor Gasoline** | | | | |
| Nitrogen Oxides NOx | 29.89 ?b | Kilogramme | Metric Tonne | Assume all emission factors are as for Road Transport Simple<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors (Tables 3-5 to 3-7: maximum values correspond to uncontrolled passenger cars)<br>c) From Bond et al, 2004 (Table 7) for gasoline, all vehicles, 'standards beginning'. |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 7.5 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 7.5 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.43 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 5.4 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 1.44 ?b | Kilogramme | Metric Tonne | |

| Demand\Transport | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| **Other or Non Specified Transport\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 38.29 ?b | Kilogramme | Metric Tonne | Assume all emission factors are as for Road Transport Simple<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factor for HDV (uncontrolled)<br>c) From Bond et al. (2004; Table 5 and Table 9) from which central values are used for the technology/emission control mix for India in the mid 1990s (i.e. if a range is given by Bond et al., then upper value taken) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 5.2 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 5.2 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 3.6 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 1.1 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.018?b | Kilogramme | Metric Tonne | |
| **Other or Non Specified Transport\LPG Liquefied Petroleum Gas** | | | | |
| Nitrogen Oxides NOx | 34.3 ?b | Kilogramme | Metric Tonne | Assume all emission factors are as for Road Transport Simple<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factor for uncontrolled passenger cars<br>c) ARIA (2008) value for LPG cars in India<br>d) Assume BC is 5.4% of PM2.5 EMEP/EEA (2016) Tier 1 emission factor, small combustion (1.A.4 , Table 3-4)<br>e) Assume OC = BC/1.3 (Bond et al, 2004; Table 5, ratio for residential LPG)) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.035 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.035 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.002 ?d | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.0015 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.108 ?b | Kilogramme | Metric Tonne | |
| **Other or Non Specified Transport\Gas and Liquids from Biomass and Wastes** | | | | |
| Nitrogen Oxides NOx | 51 ?b | Kilogramme | Terajoule | **Note: We need emission factors for biogasoline (= ethanol?) and biodiesel here**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs: CO2 and N2O as for 'Other liquid biofuels' in residential use; CH4 as for ethanol cars in Brazil.<br>b) EMEP/EEA (2016) Tier 1 defaults for small combustion (Section 1.A.4, Table 3-5)<br>c) Emission factrors needed |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.9 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 1.9 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.16 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0 ?c | Kilogramme | Terajoule | |

**References:** ARIA (2008) Emission Factor development for Indian Vehicles, The Automotive Research Association of India, Pune, India, Revision-4 March 10 2008 [http://www.cpcb.nic.in/Emission_Factors_Vehicles.pdf] Accessed 21 Jan 2014.

**Table S23:** Detailed transport emission factors use in LEAP-IBC analysis

| Fuel | Vehicle class | $NO_X$ emission factor (g/km) | $NH_3$ emission factor (g/km) | Exhaust $PM_{10}$ emission factor (g/km) | Exhaust $PM_{2.5}$ emission factor (g/km) (Assume = $PM_{10}$ emission factors) | Unpaved road dust ($PM_{10}$) emission factor in dry weather (g/km) | Unpaved road ($PM_{2.5}$) emissions factor (g/km) | BC emission factor (% of $PM_{2.5}$) | OC emission factor (OC/BC ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | Default* | Default* | Default* | Default* [l] | Default [m] | Default [n] | Default [o] | Default [o] |
| Gasoline | Passenger cars (Uncontrolled) [a] | 2.09[a] | 0.10[a] | 0.0029[a] | 0.0029[a] | 126 | 12.6 | 2 | 35 |
| Gasoline | Passenger cars (Moderate control) [d] | 1.29 | 0.002 | 0.0022 | 0.0022 | 126 | 12.6 | 30 | 1.66 |
| Gasoline | Passenger cars (Euro I) [e] | 0.485 | 0.0922 | 0.0022 | 0.0022 | 126 | 12.6 | 25 | 1.79 |
| Gasoline | Passenger cars (Euro 2) [e] | 0.255 | 0.1043 | 0.0022 | 0.0022 | 126 | 12.6 | 25 | 1.79 |
| Gasoline | Passenger cars (Euro 3) [e] | 0.097 | 0.0342 | 0.0011 | 0.0011 | 126 | 12.6 | 15 | 2.14 |
| Gasoline | Passenger cars (Euro 4) [e] | 0.061 | 0.0342 | 0.0011 | 0.0011 | 126 | 12.6 | 15 | 2.14 |
| Gasoline | Passenger cars (Euro 5) [e] | 0.061 | 0.0123 | 0.0014 | 0.0014 | 126 | 12.6 | 15 | 2.14 |
| Gasoline | Passenger cars (Euro 6) [e] | 0.061 | 0.0123 | 0.0014 | 0.0014 | 126 | 12.6 | 15 | 2.14 |
| Gasoline | Light-commercial vehicles (Conventional) [i] | 3.09 | 0.0025 | 0.0023 | 0.0023 | 225 | 22.5 | 30 | 1.66 |
| Gasoline | Light-commercial vehicles (Euro 1) i | 0.563 | 0.0758 | 0.0023 | 0.0023 | 225 | 22.5 | 25 | 1.79 |
| Gasoline | Light-commercial vehicles (Euro 2) i | 0.23 | 0.091 | 0.0023 | 0.0023 | 225 | 22.5 | 25 | 1.79 |
| Gasoline | Light-commercial vehicles (Euro 3) i | 0.129 | 0.0302 | 0.0011 | 0.0011 | 225 | 22.5 | 15 | 2.14 |
| Gasoline | Light-commercial vehicles (Euro 4) i | 0.064 | 0.0302 | 0.0011 | 0.0011 | 225 | 22.5 | 15 | 2.14 |
| Gasoline | Light-commercial vehicles (Euro 5) i | 0.064 | 0.0123 | 0.0014 | 0.0014 | 225 | 22.5 | 15 | 2.14 |
| Gasoline | Light-commercial vehicles (Euro 6) i | 0.064 | 0.0123 | 0.0012 | 0.0012 | 225 | 22.5 | 15 | 2.14 |
| Gasoline | Heavy duty (Conventional) [c] | 6.6 | 0.0019 | 0.0023 | 0.0023 | 450 | 45.0 | 30 [H] | 1.66 [H] |
| Gasoline | Motorcycles (2-stroke) (Uncontrolled)[a] | 0.375[a] | 0.0023[a] | 0.21[a] | 0.21[a] | 36 | 3.6 | 10 | 6.43 |
| Gasoline | Motorcycles (2-stroke) (Moderate control) [f] | 0.067 | 0.0019 | 0.16 | 0.16 | 36 | 3.6 | 10 | 6.43 |
| Gasoline | Motorcycles (2-stroke) (Mot-Euro 1) | 0.028 | 0.0019 | 0.064 | 0.064 | 36 | 3.6 | 20 | 2.86 |
| Gasoline | Motorcycles (2-stroke) (Mot-Euro 2) | 0.104 | 0.0019 | 0.032 | 0.032 | 36 | 3.6 | 20 | 2.86 |

| Fuel | Vehicle class | $NO_X$ emission factor (g/km) | $NH_3$ emission factor (g/km) | Exhaust $PM_{10}$ emission factor (g/km) | Exhaust $PM_{2.5}$ emission factor (g/km) (Assume = $PM_{10}$ emission factors) | Unpaved road dust ($PM_{10}$) emission factor in dry weather (g/km) | Unpaved road ($PM_{2.5}$) emissions factor (g/km) | BC emission factor (% of $PM_{2.5}$) | OC emission factor (OC/BC ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | Default* | Default* | Default* | Default* [l] | Default [m] | Default [n] | Default [o] | Default [o] |
| Gasoline | Motorcycles (2-stroke) (Mot-Euro 3) | 0.280 | 0.0019 | 0.0096 | 0.0096 | 36 | 3.6 | 20 | 2.86 |
| Gasoline | Motorcycles (4-stroke) (Uncontrolled)[a] | 0.375[a] | 0.0023[a] | 0.21[a] | 0.21[a] | 36 | 3.6 | 15 | 4.00 |
| Gasoline | Motorcycles (4-stroke) (Moderate control) [g] | 0.233 | 0.0019 | 0.014 | 0.014 | 36 | 3.6 | 15 | 4.00 |
| Gasoline | Motorcycles (4-stroke) (Mot-Euro 1) | 0.477 | 0.0019 | 0.014 | 0.014 | 36 | 3.6 | 25 | 2.14 |
| Gasoline | Motorcycles (4-stroke) (Mot-Euro 2) | 0.317 | 0.0019 | 0.0035 | 0.0035 | 36 | 3.6 | 25 | 2.14 |
| Gasoline | Motorcycles (4-stroke) (Mot-Euro 3) | 0.194 | 0.0019 | 0.0035 | 0.0035 | 36 | 3.6 | 25 | 1.79 |
| Gasoline | 3-Wheelers (2-stroke) (uncontrolled) | 0.375[b] | 0.0023[b] | 0.21[b] | 0.21[b] | 90 | 9.0 | 10 | 6.43 |
| Gasoline | 3-Wheelers (2-stroke) (Medium control) | 0.30 [A] | 0.0023[a] | 0.11[A] | 0.11[A] | 90 | 9.0 | 10 | 6.43 |
| Gasoline | 3-Wheelers (2-stroke) (Bharat 1 = Euro 1) | 0.20 [B] | 0.0023[a] | 0.045 [B] | 0.045 [B] | 90 | 9.0 | 20 | 2.86 |
| Gasoline | 3-Wheelers (2-stroke) (Bharat 2 = Euro 2) | 0.16 [C] | 0.0023[a] | 0.043 [C] | 0.043 [C] | 90 | 9.0 | 20 | 2.86 |
| Gasoline | 3-Wheelers (4-stroke) (Bharat 1 = Euro 1) | 0.61 [B] | 0.0023[a] | 0.011[B] | 0.011[B] | 90 | 9.0 | 25 | 2.14 |
| Gasoline | 3-Wheelers (4-stroke) (Bharat 2 = Euro 2) | 0.53 [C] | 0.0023[a] | 0.015 [C] | 0.015 [C] | 90 | 9.0 | 25 | 2.14 |
| Diesel | 3-Wheelers (Moderate control) | 0.93 [A] | 0.001 | 0.782 [A] | 0.782 [A] | 90 | 9.0 | 55 | 0.5 |
| Diesel | 3-Wheelers (Bharat 1 = Euro 1) | 0.69 [B] | 0.001 | 0.347 [B] | 0.347 [B] | 90 | 9.0 | 70 | 0.29 |
| Diesel | 3-Wheelers (Bharat 2 = Euro 2) | 0.51 [C] | 0.001 | 0.091 [C] | 0.091 [C] | 90 | 9.0 | 80 | 0.16 |
| Diesel | Passenger cars (Conventional) [h] | 0.546 | 0.001 | 0.2209 | 0.2209 | 126 | 12.6 | 55 | 0.5 |
| Diesel | Passenger cars (Euro 1) [h] | 0.690 | 0.001 | 0.0842 | 0.0842 | 126 | 12.6 | 70 | 0.29 |
| Diesel | Passenger cars (Euro 2) [h] | 0.716 | 0.001 | 0.0548 | 0.0548 | 126 | 12.6 | 80 | 0.16 |
| Diesel | Passenger cars (Euro 3) [h] | 0.773 | 0.001 | 0.0391 | 0.0391 | 126 | 12.6 | 85 | 0.11 |
| Diesel | Passenger cars (Euro 4) [h] | 0.58 | 0.001 | 0.0314 | 0.0314 | 126 | 12.6 | 87 | 0.09 |
| Diesel | Passenger cars (Euro 5) [h] | 0.55 | 0.0019 | 0.0021 | 0.0021 | 126 | 12.6 | 10 | 1.43 |

| Fuel | Vehicle class | $NO_X$ emission factor (g/km) | $NH_3$ emission factor (g/km) | Exhaust $PM_{10}$ emission factor (g/km) | Exhaust $PM_{2.5}$ emission factor (g/km) (Assume = $PM_{10}$ emission factors) | Unpaved road dust ($PM_{10}$) emission factor in dry weather (g/km) | Unpaved road ($PM_{2.5}$) emissions factor (g/km) | BC emission factor (% of $PM_{2.5}$) | OC emission factor (OC/BC ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | Default* | Default* | Default* | Default* [l] | Default [m] | Default [n] | Default [o] | Default [o] |
| Diesel | Passenger cars (Euro 6) [h] | 0.45 | 0.0019 | 0.0015 | 0.0015 | 126 | 12.6 | 20 | 1.43 |
| Diesel | Light-commercial vehicles (Conventional) i | 1.66 | 0.0012 | 0.356 | 0.356 | 225 | 22.5 | 55 | 0.5 |
| Diesel | Light-commercial vehicles (Euro 1) i | 1.22 | 0.0012 | 0.117 | 0.117 | 225 | 22.5 | 70 | 0.29 |
| Diesel | Light-commercial vehicles (Euro 2) i | 1.22 | 0.0012 | 0.117 | 0.117 | 225 | 22.5 | 80 | 0.16 |
| Diesel | Light-commercial vehicles (Euro 3) i | 1.03 | 0.0012 | 0.0783 | 0.0783 | 225 | 22.5 | 85 | 0.11 |
| Diesel | Light-commercial vehicles (Euro 4) i | 0.831 | 0.0012 | 0.0409 | 0.0409 | 225 | 22.5 | 87 | 0.09 |
| Diesel | Light-commercial vehicles (Euro 5) i | 1.15 | 0.0019 | 0.001 | 0.001 | 225 | 22.5 | 10 | 1.43 |
| Diesel | Light-commercial vehicles (Euro 6) i | 0.96 | 0.0019 | 0.0009 | 0.0009 | 225 | 22.5 | 20 | 1.43 |
| Diesel | Heavy-duty vehicles (Conventional) [j] | 8.92 | 0.0029 | 0.333 | 0.3344 | 450 | 45.0 | 50 | 0.57 |
| Diesel | Heavy-duty vehicles (HD Euro I) [j] | 5.31 | 0.0029 | 0.129 | 0.201 | 450 | 45.0 | 65 | 0.29 |
| Diesel | Heavy-duty vehicles (HD Euro II) [j] | 5.5 | 0.0029 | 0.061 | 0.104 | 450 | 45.0 | 65 | 0.29 |
| Diesel | Heavy-duty vehicles (HD Euro III) [j] | 4.3 | 0.0029 | 0.0566 | 0.0881 | 450 | 45.0 | 70 | 0.21 |
| Diesel | Heavy-duty vehicles (HD Euro IV) [j] | 2.65 | 0.0029 | 0.0106 | 0.0161 | 450 | 45.0 | 75 | 0.14 |
| Diesel | Heavy-duty vehicles (HD Euro V) [j] | 1.51 | 0.011 | 0.0106 | 0.0161 | 450 | 45.0 | 75 | 0.14 |
| Diesel | Heavy-duty vehicles (HD Euro VI) [j] | 0.291 | 0.011 | 0.0005 | 0.0008 | 450 | 45.0 | 15 | 2.14 |
| Diesel | Urban Buses (Conventional) [j] | 16.5 | 0.0029 | 0.909 | 0.909 | 450 | 45.0 | 50 | 0.57 |
| Diesel | Urban buses (HD Euro I) [k] | 10.1 | 0.0029 | 0.479 | 0.479 | 450 | 45.0 | 65 | 0.57 |
| Diesel | Urban buses (HD Euro II) [k] | 10.7 | 0.0029 | 0.22 | 0.22 | 450 | 45.0 | 65 | 0.29 |
| Diesel | Urban buses (HD Euro III) [k] | 9.38 | 0.0029 | 0.207 | 0.207 | 450 | 45.0 | 70 | 0.21 |
| Diesel | Urban buses (HD Euro IV) [k] | 5.42 | 0.0029 | 0.0462 | 0.0462 | 450 | 45.0 | 75 | 0.14 |
| Diesel | Urban buses (HD Euro V) [k] | 3.09 | 0.0029 | 0.0462 | 0.0462 | 450 | 45.0 | 75 | 0.14 |
| Diesel | Urban buses (HD Euro VI) [k] | 0.597 | 0.0029 | 0.0023 | 0.0023 | 450 | 45.0 | 15 | 2.14 |

| Fuel | Vehicle class | $NO_X$ emission factor (g/km) | $NH_3$ emission factor (g/km) | Exhaust $PM_{10}$ emission factor (g/km) | Exhaust $PM_{2.5}$ emission factor (g/km) (Assume = $PM_{10}$ emission factors) | Unpaved road dust ($PM_{10}$) emission factor in dry weather (g/km) | Unpaved road ($PM_{2.5}$) emissions factor (g/km) | BC emission factor (% of $PM_{2.5}$) | OC emission factor (OC/BC ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | Default* | Default* | Default* | Default* [l] | Default [m] | Default [n] | Default [o] | Default [o] |
| CNG | 3-wheeler (Bharat 1 = Euro 1) | 0.50 [B] | 0.034 | 0.015 [B] | 0.015 [B] | 90 | 9.0 | | |
| CNG | 3-wheeler Retrofit (Bharat 1 = Euro 1) | 0.19 [B] | 0.034 | 0.118 [B] | 0.118 [B] | 90 | 9.0 | | |
| CNG | Passenger car retrofit (moderate control) | 0.53 [A] | 0.034 | 0.001 [A] | 0.001 [A] | 126 | 12.6 | | |
| CNG | Passenger car retrofit (Bharat 1 = Euro 1) | 0.01 [B] | 0.034 | 0.002 [B] | 0.002 [B] | 126 | 12.6 | | |
| CNG | Passenger car (Euro 4 and later) | 0.056 | 0.034 | 0.0011 | 0.0011 | 126 | 12.6 | | |
| CNG | Urban Bus (HD Euro I) | 16.5 | n.a. | 0.02 | 0.02 | 450 | 45.0 | | |
| CNG | Urban Bus (HD Euro II) | 15 | n.a. | 0.01 | 0.01 | 450 | 45.0 | | |
| CNG | Urban Bus (HD Euro III) | 10 | n.a. | 0.01 | 0.01 | 450 | 45.0 | | |
| LPG | 3-wheeler Retrofit (Moderate control) [A] | 0.05 [A] | 0.002 [E] | 0.171 [A] | 0.171 [A] | 90 | 9.0 | | |
| LPG | 3-wheeler Retrofit (Bharat 1 = Euro 1) | 0.04 [B] | 0.088 [E] | 0.130 [B] | 0.130 [B] | 90 | 9.0 | | |
| LPG | Passenger cars (Conventional) | 2.36 | 0.0020 | 0.0022 | 0.0022 | 126 | 12.6 | | |
| LPG | Passenger cars (Euro 1) | 0.414 | 0.0880 | 0.0022 | 0.0022 | 126 | 12.6 | | |
| LPG | Passenger cars (Euro 2) | 0.18 | 0.1007 | 0.0022 | 0.0022 | 126 | 12.6 | | |
| LPG | Passenger cars (Euro 3) | 0.09 | 0.0338 | 0.0011 | 0.0011 | 126 | 12.6 | | |
| LPG | Passenger cars (Euro 4) | 0.056 | 0.0338 | 0.0011 | 0.0011 | 126 | 12.6 | | |
| LPG | Passenger cars (Euro 5) | 0.056 | 0.0338 | 0.0011 | 0.0011 | 126 | 12.6 | | |
| LPG | Passenger cars (Euro 6) | 0.056 | 0.0338 | 0.0011 | 0.0011 | 126 | 12.6 | | |
| LPG | Light-duty vehicles (Uncontrolled) | 2.1 [F] | 0.002 [E] | 0.0022 [E] | 0.0022 [E] | 225 | 22.5 | | |
| LPG | Light-duty vehicles (Good control - Euro-I) | 0.05 [F] | 0.088 [E] | 0.0022 [E] | 0.0022 [E] | 225 | 22.5 | | |
| LPG | Heavy-duty vehicles (Uncontrolled) | 5.7 [G] | 0.004 [E] | 0.0044 [E] | 0.0044 [E] | 450 | 45.0 | | |
| LPG | Heavy-duty vehicles (Good contro) | 2.6 [G] | 0.176 [E] | 0.0044 [E] | 0.0044 [E] | 450 | 45.0 | | |

## Remark:

*** Emission factors are Tier 2 exhaust emission factors from EMEP/EEA (2016), Tables 3-17 to 3-26, unless otherwise indicated.**

[a] Uncontrolled EFs = Tier 1 maximum value from EMEP/EEA (2016) converted assuming fuel economy from Table 3-15, EMEP/EEA, 2016

[b] Assume = Motorcycle 2-stroke (uncontrolled)

[c] Heavy duty vehicle, Gasoline, >3.5 t weight.

[d] Emission factors for Petrol Medium passenger cars (1.4 - 2.0 L engine capacity), Open loop technology (from EMEP/EEA (2016), Tables 3-17 and 3-18)

[e] Emission factors for Petrol Medium passenger cars (1.4 - 2.0 L engine capacity) from EMEP/EEA (2016) Tier 2 exhaust emission factors, Tables 3-17 and 3-18.

[f] Emission factors for 2-stroke motorcycles (>50 $cm^3$), 'Conventional' technology (from EMEP/EEA (2016), Tables 3-24 and 3-25)

[g] Emission factors for 4-stroke motorcycles (250 - 750 $cm^3$), 'Conventional' technology (from EMEP/EEA (2016), Tables 3-24 and 3-25)

[h] Emission factors for Diesel Medium passenger cars (1.4 - 2.0 L engine capacity) from EMEP/EEA (2016) Tier 2 exhaust emission factors, Tables 3-17 and 3-18.

[i] Emission factors for Light Commercial Vehicles (<3.5 t weight) from EMEP/EEA (2016) Tier 2 exhaust emission factors, Tables 3-19 and 3-20.

[j] Emission factors for Heavy Duty Vehicles (7.5 - 16 t weight) from EMEP/EEA (2016) Tier 2 exhaust emission factors, Tables 3-21 and 3-22

[k] Urban buses standard - vehicles used for the carriage of passengers and comprising more than eight seats in addition to the driver's seat

[l] Assume PM2.5 EF = PM10 EF

[m] Derived from Gillies et.al. (2005) for unpaved rural roads in dry weather (roadbed moisture content <0.5%; assume = to days when precipitation is < 0.25 mm; silt content range 4% - 7%). **Emission factor = 3 x W x S g/km** where S is the average speed in km/hr and W is the average vehicle wieght in tonnes. Factors suggested assume 30 km average speed for all vehicles and average weights of 0.4 t for 2-wheelers, 1 t for 3-wheelers, 1.4 t for passenger cars, 2.5 t for light commercial vehicles and 5 t for heavy duty vehicles (trucks and buses). If the average weight or average speed for a vehicle class differ from these assumptions then the formula should be used to calculate revised factors.

[n] Assume PM2.5 factor is 10% of PM10 factor (USEPA, 2006)

[o] EMEP/EEA (2016) Tier 3 fraction BC (%) and Organic matter (OM) to BC ratio (Table 3-91 in July 2018 update) assuming OM = 1.4xOC

[A] ARAI (2008) value for Indian fleet 1996-2000

[B] ARAI (2008) value for Indian fleet post 2000 (Bharat 1 = Euro 1)

[C] ARAI (2008) value for Indian fleet post 2005 (Bharat 2 = Euro 2)

[D] IPCC (2006) default EF for European vehicles

[E] Assume LDV = passenger car; HDV = 2 x passenger car

[F] IPCC (1996) default EF for US LPG passenger cars

[G] IPCC (1996) default EF for US LPG uncontrolled heavy duty vehicles with stoichiometric engine

[H] Assume = LCV (Conventional)

**Table S24:** Residential emission factors for use in LEAP-IBC analysis

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| **Demand\Residential\Cooking** | | | | |
| **Cooking\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 51 ?a | Kilogramme | Terajoule | a) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.4)<br>b) EMEP/EEA (2016) Tier 1 emission factor - 5.4% of PM2.5<br>c) Assume OC = 8.33 x BC (Bond et al., 2004)<br>d) IPCC 2006 Guidelines - Tier 1 default Efs<br>e) Battye et al. (1994) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.2 ?a | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 1.2 ?a | Kilogramme | Terajoule | |
| Black Carbon | 0.065 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.54 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.01 ?e | Kilogramme | Metric Tonne | |
| **Cooking\Kerosene** | | | | |
| Nitrogen Oxides NOx | 1.10 ?a | Kilogramme | Metric Tonne | a) Zhang et al. (2000) Average EF for household stoves in China.<br>b) Assume a PM2.5/PM ratio of 0.964 for kerosene. Reddy and Venkataraman (2002a)<br>c) Assume 13% of PM10 - Bond et al (2004) Table 5<br>d) Assume 10% of PM10 - Bond et al (2004) Table 5<br>e) IPCC 2006 Guidelines - Tier 1 default EFs<br>f) Assume as for industry |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.134 ?a | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.129 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.017 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.013 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.005 ?f | Kilogramme | Terajoule | |
| **Cooking\LPG** | | | | |
| Nitrogen Oxides NOx | 51 ?d | Kilogramme | Terajoule | a) For LPG Indian stove. Venkataraman et al (2010)<br>b) Assume a PM2.5/PM ratio 0.964 for LPG. Reddy and Venkataraman (2002a)<br>c) IPCC 2006 Guidelines - Tier 1 default EFs<br>d) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.4)<br>e) Assume as for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.32 ?a | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.31 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.01 ?a | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.06 ?a | Kilogramme | Metric Tonne | |
| Ammonia | 0.01 ?e | Kilogramme | Terajoule | |
| **Cooking\Traditional Stove Charcoal** | | | | |

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Nitrogen Oxides NOx | 2.16 ?b | Kilogramme | Metric Tonne | a) Akagi et al (2011)<br>b) Bertschi et al. (2003) for charcoal cooking fires (in Zambia).)<br>c) Smith et al (2000) - For PM assume = TSP value<br>d) Assume 50% of PM is BC and 50% POM (i.e. OCx1.4) Bond et al. (2004) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 2.38 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 2.38 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 1.19 ?d | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.85 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.97 ?b | Kilogramme | Metric Tonne | |
| **Cooking\Traditional Stove Wood** | | | | |
| Nitrogen Oxides NOx | 2.18 ?c | Kilogramme | Metric Tonne | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Bertschi et al (2003)<br>c) Akagi et al (2011) (For NOx converted from 'as NO' to as 'NO2')<br>d) Assume PM2.5 = 80% of PM10 as reported for wood and crop waste by Reddy and Venkataraman (2002b) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 8.3 ?d | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 6.64 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.83 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 2.89 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.87 ?c | Kilogramme | Metric Tonne | |
| **Cooking\Traditional Stove Vegetal Wastes** | | | | |
| Nitrogen Oxides NOx | 47 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Zhang et al. (2000) Average EF for household stoves in China. (For 'vegetal materials and waste', EF = average for wheat and maize residues)<br>c) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.6)<br>d) Assuming PM2.5/PM ratio of 0.8 as reported for wood and crop waste (Reddy and Venkataraman, 2002b)<br>e) From Bond et al. (2004) Tables 9 and 10<br>f) Bertschi et al. (2003) [Zambian open fires] |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 8.05 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 6.44 ?d | Kilogramme | Metric Tonne | |
| Black Carbon | 1.0 ?e | Kilogramme | Metric Tonne | |
| Organic Carbon | 3.3 ?e | Kilogramme | Metric Tonne | |
| Ammonia | 1.29 ?f | Kilogramme | Metric Tonne | |
| **Cooking\Improved Biomass Stove with Chimney** | | | | |
| Nitrogen Oxides NOx | 50 ?b | Kilogramme | Terajoule | a) Akagi et al (2011) mean for Patsari stoves with chimney<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.6)<br>c) Johnson et al (2008) mean values for 5 different types of Patsari cookstoves with chimney (N=30)<br>d) Calculated as BC + (OC x 1.3) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 4.05 ?g | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 3.24 ?d | Kilogramme | Metric Tonne | |
| Black Carbon | 0.74 ?c | Kilogramme | Metric Tonne | |

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Organic Carbon | 1.92 ?c | Kilogramme | Metric Tonne | e) NH3 value for Patsari cooking stove (Christian et al. 2010)<br>f) IPCC 2006 Guidelines - Tier 1 default EFs<br>g) Assume PM2.5 = 80% of PM10 as reported for wood and crop waste by Reddy and Venkataraman (2002) |
| Ammonia | 0.03 ?e | Kilogramme | Metric Tonne | |
| **Cooking\Traditional Stove Animal Wastes** | | | | |
| Nitrogen Oxides NOx | 0.77 ?b | Kilogramme | Metric Tonne | a) For Dung fuel in Indian stove. Venkataraman et al (2010)<br>b) Keene et al (2006)<br>c) Akagi et al (2011) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.0 ?a | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 3.0 ?a | Kilogramme | Metric Tonne | |
| Black Carbon | 0.12 ?a | Kilogramme | Metric Tonne | |
| Organic Carbon | 1.8 ?a | Kilogramme | Metric Tonne | |
| Ammonia | 4.75 ?c | Kilogramme | Metric Tonne | |
| **Cooking\Fan Assisted Biomass Stove** | | | | |
| Nitrogen Oxides NOx | 50 ?e | Kilogramme | Terajoule | a) Mean of high and low values given for Philips HD4012 (Made by African Clean Energy PTY Ltd., $89) details from http://catalog.cleancookstoves.org/#/stoves/47<br>b) Assume x 1.25 of PM2.5 value (i.e. PM2.5/PM ratio of 0.8 as reported for wood and crop waste by Reddy and Venkataraman (2002b))<br>c) Assume BC:OC ratio same as for traditional woodstove<br>d) IPCC (2006) Tier 1<br>e) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.6) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.75 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.60 ?a | Kilogramme | Metric Tonne | |
| Black Carbon | 0.12 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.34 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0 | Kilogramme | Terajoule | |
| **Demand\Residential\Lighting** | | | | |
| **Lighting\Simple Wick Kerosene Lamps** | | | | |
| Nitrogen Oxides NOx | 25 ?c | Kilogramme | Terajoule | a) Lam et al (2012) Simple wick kersosene lamp - typical field use<br>b) IPCC Guidelines (IPCC, 1996), Reference Manual, Tier 1<br>c) Zhang et al. (2000) Average EF for household stoves in China.<br>d) IPCC (2006) Tier 1 default |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 93 ?a | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 93 ?a | Kilogramme | Metric Tonne | |
| Black Carbon | 90 ?a | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.4 ?a | Kilogramme | Metric Tonne | |
| Ammonia | 0 | Kilogramme | Terajoule | |

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| **Lighting\Hurricane Kerosene Lamps** | | | | |
| Nitrogen Oxides NOx | 25 ?c | Kilogramme | Terajoule | a) Lam et al (2012) Hurricane kersosene lamp - typical field use<br>b) IPCC Guidelines (IPCC, 1996), Reference Manual, Tier 1<br>c) Zhang et al. (2000) Average EF for household stoves in China.<br>d) IPCC (2006) Tier 1 default |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 13 ?a | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 13 ?a | Kilogramme | Metric Tonne | |
| Black Carbon | 9 ?a | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.5 ?a | Kilogramme | Metric Tonne | |
| Ammonia | 0 | Kilogramme | Terajoule | |
| **Lighting\LPG** | | | | |
| Nitrogen Oxides NOx | 51?b | Kilogramme | Terajoule | a) IPCC (2006) Tier 1 default<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assume OC = 6xBC as for LPG Indian stove. Venkataraman et al (2010) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.9 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 1.9 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.16 ?b | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.97 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0 | Kilogramme | Terajoule | |
| **Demand\Residential\Other** | | | | |
| **Residential\Other\Other Bituminous Coal and Anthracite** | | | | |
| Nitrogen Oxides NOx | 1.5 ?a | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Zhang et al. (2000) Average EF for household stoves in China.<br>c) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.3)<br>d) Zhi et al. (2008) value for bituminous coal burnt in a high efficiency chunk (HEC) stove.<br>e) Assume a PM2.5/PM ratio of 0.9 for coal. Reddy and Venkataraman (2002a)<br>f) Zhi et al. (2008) value for bituminous coal burnt in a high efficiency chunk (HEC) stove. Calculated from EC factor of 3.81 (from Table 1) times OC/EC ratio of 0.58 (from Table 3)<br>g) From Li et al (2016) - Value of 1.17 is for bituminous chunk coal in traditional stove (use 0.10 for advanced stove). For anthracite chunk use 0.20 |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 14.8 ?d | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 13.3 ?e | Kilogramme | Metric Tonne | |
| Black Carbon | 2.2 ?f | Kilogramme | Metric Tonne | |
| Organic Carbon | 5.93 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 1.17 ?g | Kilogramme | Metric Tonne | |

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| **Residential\Other\BKB Brown coal briquettes** | | | | |
| Nitrogen Oxides NOx | 1.5 ?a | Kilogramme | Terajoule | Assume all emission factors are as for Honeycomb Briquettes |
| Nitrous Oxide | 34 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{10}$ | 7.33 ?d | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 6.6 ?e | Kilogramme | Metric Tonne | |
| Black Carbon | 0.137 ?f | Kilogramme | Metric Tonne | |
| Organic Carbon | 4.16 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.70 ?g | Kilogramme | Metric Tonne | |
| **Residential\Other\Honeycomb briquettes** | | | | |
| Nitrogen Oxides NOx | 1.5 ?a | Kilogramme | Terajoule | a), b) and c) Assume as for Other Bituminous Coal and Anthracite<br>d) Zhi et al. (2008) value for honeycomb-coal-briquette burnt in a high efficiency briquette (HEB) stove.<br>e) Assume a PM2.5/PM ratio of 0.9 for coal. Reddy and Venkataraman (2002a)<br>f) Zhi et al. (2008) value for honeycomb-coal-briquette burnt in a high efficiency briquette (HEB) stove. Calculated from EC factor of 0.082 (from Table 1) times OC/EC ratio of 1.67 (from Table 3)<br>g) From Li et al (2016) - NH3 Value of 0.70 is for anthracite briquette in traditional stove (use 0.06 for advanced stove). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 7.33 ?d | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 6.6 ?e | Kilogramme | Metric Tonne | |
| Black Carbon | 0.137 ?f | Kilogramme | Metric Tonne | |
| Organic Carbon | 4.16 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.70 ?g | Kilogramme | Metric Tonne | |
| **Residential\Other\Coke Oven Gas** | | | | |
| Nitrogen Oxides NOx | 51 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.4)<br>c) Assume OC = 8.33 x BC as for natural gas in Bond et al, (2004) Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 1.2 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.065 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.54 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.01 ?d | Kilogramme | Metric Tonne | |
| **Residential\Other\Gas Works Gas** | | | | |
| Nitrogen Oxides NOx | 51 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.4)<br>c) Assume OC = 8.33 x BC as for natural gas in Bond et al, (2004) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.2 ?b | Kilogramme | Terajoule | |

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{2.5}$ | 1.2 ?b | Kilogramme | Terajoule | Table 5<br>d) Assume = factor for natural gas |
| Black Carbon | 0.065 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.54 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.01 ?d | Kilogramme | Metric Tonne | |
| **Residential\Other\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 51 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.4)<br>c) Assume OC = 8.33 x BC (Bond et al., 2004, Table 5)<br>d) Battye et al. (1994) defaults (no NOx controls) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 1.2 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.065 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.54 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.01 ?d | Kilogramme | Metric Tonne | |
| **Residential\Other\LPG** | | | | |
| Nitrogen Oxides NOx | 51 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.4)<br>c) Venkataraman et al (2010) for Indian LPG Cookstove<br>d) Assume a PM2.5/PM ratio 0.964 for LPG. Reddy and Venkataraman (2002a)<br>e) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.32 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.31 ?d | Kilogramme | Metric Tonne | |
| Black Carbon | 0.001 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.06 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.01 ?e | Kilogramme | Metric Tonne | |
| **Residential\Other\Motor Gasoline** | | | | |
| Nitrogen Oxides NOx | 306 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for commercial/institutional liquid fuels (1.A.4, Table 3.9)<br>c) Assume OC = BC/3.5 (Bond et al., 2004 Tables 9 and 10)<br>d) Assume as for industry |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 21 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 18 ?b | Kilogramme | Terajoule | |
| Black Carbon | 10.1 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 2.89 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| **Residential\Other\Kerosene** | | | | |
| Nitrogen Oxides NOx | 306 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for commercial/institutional, liquid fuels (1.A.4, Table 3.9)<br><br>c) Assume OC = BC/3.5 (Bond et al., 2004 Tables 9 and 10) d) Assume = gasoline |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 21 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 18 ?b | Kilogramme | Terajoule | |
| Black Carbon | 10.1 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 2.89 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Residential\Other\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 942 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 2 emission factors for reciprocating engines (Table 3-31)<br>c) From Klimont et al (2017) (Table S3.1) GAINS emission factors for diesel generators (no control) d) Assume as for industry |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 96 ?c | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 96 ?c | Kilogramme | Terajoule | |
| Black Carbon | 40 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 28 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Residential\Other\Wood** | | | | |
| Nitrogen Oxides NOx | 2.18 ?c | Kilogramme | Metric Tonne | **Assume same as for Cooking/Traditional Stove Wood**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Bertschi et al (2003)<br>c) Akagi et al (2011) (For NOx converted from 'as NO' to as 'NO2')<br>d) Assume PM2.5 = 80% of PM10 as reported for wood and crop waste by Reddy and Venkataraman (2002) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 8.3 ?d | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 6.64 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.83 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 2.89 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.87 ?c | Kilogramme | Metric Tonne | |
| **Residential\Other\Vegetal Wastes** | | | | |
| Nitrogen Oxides NOx | 47 ?b | Kilogramme | Terajoule | **Assume same as for Cooking/Traditional Stove Vegetal Wastes**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Zhang et al. (2000) Average EF for household stoves in China. (For 'vegetal materials and waste', EF = average for wheat and maize |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 8.05 ?b | Kilogramme | Metric Tonne | |

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{2.5}$ | 6.44 ?d | Kilogramme | Metric Tonne | residues)<br>c) EMEP/EEA (2013) Tier 1 emission factor (1.A.4 Small combustion, Table 3.6)<br>d) Assuming PM2.5/PM ratio of 0.8 as reported for wood and crop waste (Reddy and Venkataraman, 2002b)<br>e) From Bond et al. (2004) Tables 9 and 10<br>f) From Li et al (2016) - Value of 0.91 is the mean for three types of biomass briquette in traditional stove (use 0.17 for advanced stove). |
| Black Carbon | 1.0 ?e | Kilogramme | Metric Tonne | |
| Organic Carbon | 3.3 ?e | Kilogramme | Metric Tonne | |
| Ammonia | 0.91 ?f | Kilogramme | Metric Tonne | |
| **Residential\Other\Animal Wastes** | | | | |
| Nitrogen Oxides NOx | 0.77 ?b | Kilogramme | Metric Tonne | **Assume same as for Cooking/Traditional Stove Animal Wastes**<br>a) For Dung fuel in Indian stove. Venkataraman et al (2010)<br>b) Keene et al (2006)<br>c) Akagi et al (2011) |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.0 ?a | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 3.0 ?a | Kilogramme | Metric Tonne | |
| Black Carbon | 0.12 ?a | Kilogramme | Metric Tonne | |
| Organic Carbon | 1.8 ?a | Kilogramme | Metric Tonne | |
| Ammonia | 4.75 ?c | Kilogramme | Metric Tonne | |
| **Residential\Other\Unspecified Primary Solid Biomass** | | | | |
| Nitrogen Oxides NOx | 2.18 ?c | Kilogramme | Metric Tonne | **Assume same as for Cooking/Traditional Stove Wood**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Bertschi et al (2003)<br>c) Akagi et al (2011) (For NOx converted from 'as NO' to as 'NO2')<br>d) Assume PM2.5 = 80% of PM10 as reported for wood and crop waste by Reddy and Venkataraman (2002) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 8.3 ?d | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 6.64 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.83 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 2.89 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.87 ?c | Kilogramme | Metric Tonne | |
| **Residential\Other\Biogas** | | | | |
| Nitrogen Oxides NOx | 51 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.4)<br>c) Assume = TSP value given by Smith, Kirk R. et al, (2000) for biogas.<br>d) Assume BC and OC fractions are as for natural gas in Bond et al (2004): Table 5<br>e) Assume as for natural gas, Battye et al. (1994) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.53 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.53 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.031 ?d | Kilogramme | Metric Tonne | |

| Demand\Residential | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Organic Carbon | 0.26 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.01 ?e | Kilogramme | Metric Tonne | |
| **Residential\Other\Charcoal** | | | | |
| Nitrogen Oxides NOx | 2.16 ?b | Kilogramme | Metric Tonne | **Assume same as for Cooking/Traditional Stove Charcoal**<br>a) Akagi et al (2011)<br>b) Bertschi et al. (2003) for charcoal cooking fires (in Zambia).)<br>c) Smith et al (2000) - For PM assume = TSP value<br>d) Assume 50% of PM is BC and 50% POM (i.e. OCx1.4) Bond et al. (2004) |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 2.38 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 2.38 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 1.19 ?d | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.85 ?d | Kilogramme | Metric Tonne | |
| Ammonia | 0.97 ?b | Kilogramme | Metric Tonne | |

**Table S25:** Brick Kilns emission factors use in LEAP-IBC analysis

| Demand\Brick Kilns | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| **Traditional kilns\Other Bituminous Coal and Anthracite** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-2)<br>c) Value for 100% coal-fueled Bull's trench brick kiln from Weyant et al. (2014)<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*($SO_2$/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 4.1 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 3.7 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 2.7 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.11 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Traditional kilns\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Traditional kilns\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/diesel fuel (high end of range) in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.6 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Traditional kilns\Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |

| Demand\Brick Kilns | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | c) Assuming BC/OC ratio as for industry/diesel fuel (high end of range) in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 4.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Traditional kilns\Primary solid biomass** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | a) Mean of range given by Christian et al (2010) for wood waste (90% sawdust) in "traditional-fixed" kilns in Mexico<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-5)<br>c) IPCC 2006 Guidelines - Tier 1 default EFs<br>d) Assume PM10 = PM2.5 factor |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.6 ?d | Kilogramme | Metric tonne | |
| Particulates $PM_{2.5}$ | 1.6 ?a | Kilogramme | Metric tonne | |
| Black Carbon | 1.05 ?a | Kilogramme | Metric tonne | |
| Organic Carbon | 0.356 ?a | Kilogramme | Metric tonne | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |
| **Traditional kilns\Industrial waste** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>Assume the rest are the same as for Primary solid biomass:<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-5)<br>c) Assuming all PM2.5 is either BC or OC<br>d) Not known - emission factor needed |
| Sulfur Dioxide | 11 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{10}$ | 143 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 140 ?b | Kilogramme | Terajoule | |
| Black Carbon | 39.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 72 ?c | Kilogramme | Terajoule | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |
| **Improved Kilns_Zigzag_Hoffman_VSBK** | | | | |
| **Improved Kilns_Zigzag_Hoffman_VSBK\Other Bituminous Coal and Anthracite** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-2)<br>c) Mean of 3 values for Forced Draft Zig-Zag (FDZ) kiln reported by Weyant et al., 2014. For VSBK use 96.7 t/TJ for CO2, 2969 kg/TJ for CO, 1.3 kg/t for PM2.5, 0.06 kg/t for BC and 0.69 kg/t for OC.<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 1.03 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 0.93 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.223 ?c | Kilogramme | Metric Tonne | |

| Demand\Brick Kilns | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Organic Carbon | 0.11?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Improved Kilns_Zigzag_Hoffman_VSBK\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Improved Kilns_Zigzag_Hoffman_VSBK\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/diesel fuel (high end of range) in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.6 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Improved Kilns_Zigzag_Hoffman_VSBK\Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 4.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Improved Kilns_Zigzag_Hoffman_VSBK\Primary solid biomass** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | |

| Demand\Brick Kilns | Emission factor | Units | Per… | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | **Primary solid biomass = wood, vegetal materials/wastes, animal prodcuts/wastes, and charcoal**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-5)<br>c) EFs for MK2 improved biomass kiln from 2013 SLCF Field Campaign, Mexico |
| Particulates $PM_{10}$ | 1.94 ?c | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 1.94 ?c | Kilogramme | Metric Tonne | |
| Black Carbon | 0.15 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.03 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |
| **Improved Kilns_Zigzag_Hoffman_VSBK\Industrial waste** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>Assume the rest are the same as for Primary solid biomass:<br>b) EMEP/EEA (2013) Tier 1 emission factors for combustion (1.A.2, Table 3-5)<br>c) Assuming all PM2.5 is either BC or OC |
| Sulfur Dioxide | 11 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{10}$ | 143 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 140 ?b | Kilogramme | Terajoule | |
| Black Carbon | 39.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 72 ?c | Kilogramme | Terajoule | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |

**Table S26:** Manufacturing and Construction emission factors use in LEAP-IBC analysis

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Iron and Steel\Coke Oven Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\Blast Furnace Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\Gas Works Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\LPG Liquefied Petroleum gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/diesel fuel (high end of range) in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.6 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 4.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\Petroleum Coke** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/heavy fuel oil (high end of range) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | in Bond et al (2004): Tables 9 & 10<br>d) Assume as for coal |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 4.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\Non_specified petroleum products** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | Assume as for Gas Diesel<br><br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/diesel fuel (high end of range) in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates PM10 | 20 ?b | Kilogramme | Terajoule | |
| Particulates PM2.5 | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.6 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Iron and Steel\Charcoal** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | Primary solid biomass = wood, vegetal materials/wastes, animal prodcuts/wastes, and charcoal<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-5)<br>c) Assuming all PM2.5 is either BC or OC |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 143 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 140 ?b | Kilogramme | Terajoule | |
| Black Carbon | 39.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 72 ?c | Kilogramme | Terajoule | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Demand\Manufacturing and Construction\Combustion Other Industries_Excludes Brick Kilns** | | | | |
| **Combustion Other Industries_Excludes Brick Kilns\Coking Coal** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-2)<br>c) Assuming BC/OC ratio for industry/hard coal (upper end of range) in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 117 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 108 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.9 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 5.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Other Bituminous Coal and Anthracite** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-2)<br>c) Assuming BC/OC ratio for industry/hard coal (upper end of range) in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 117 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 108 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.9 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 5.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Sub Bituminous Coal** | | | | |
| Nitrogen Oxides NOx | 173 * (100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | 3-2)<br>c) Assuming BC/OC ratio as in Bond et al (2004) Tables 9 and 10 - upper end of range for Industry/brown coal<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Particulates $PM_{10}$ | 117 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 108 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.9 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 31.3 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Lignite** | | | | |
| Nitrogen Oxides NOx | 173 * (100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-2)<br>c) Assuming BC/OC ratio as in Bond et al (2004) Tables 9 and 10 - upper end of range for Industry for brown coal<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 117 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 108 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.9 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 31.3 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Patent fuel** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-2)<br>c) Assuming BC/OC ratio as in Bond et al (2004) Tables 9 and 10 - upper |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{10}$ | 117 ?b | Kilogramme | Terajoule | end of range for Industry for hard coal<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Particulates $PM_{2.5}$ | 108 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.9 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 5.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Coke Oven Coke** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-2)<br>c) Assuming BC/OC ratio as in Bond et al (2004) Tables 9 and 10 - for Industry<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 117 * (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 108 * (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.91 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 11.1 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\BKB Brown Coal Briquettes** | | | | |
| Nitrogen Oxides NOx | 173 * (100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-2)<br>c) Assuming BC/OC ratio as in Bond et al (2004) Tables 9 and 10 - upper end of range for Industry<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 117 * (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{2.5}$ | 108 * (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.9 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 31.3 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Coke Oven Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Blast Furnace Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Combustion Other Industries_Excludes Brick Kilns\Gas Works Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Battye et al. (1994) defaults (no NOx controls) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Crude Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for Heavy Fuel Oil from Bond et al (2004): Tables 9 & 10<br>d) Assume as for Heavy Fuel Oil |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 4.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Terajoule | |
| **Combustion Other Industries_Excludes Brick Kilns\Refinery Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-**3**)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\LPG Liquefied Petroleum gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-3)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Combustion Other Industries_Excludes Brick Kilns\Motor Gasoline** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/gasoline in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Kerosene** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/kerosene in Bond et al (2004): Tables 9 & 10<br>d) Assume as for motor gasoline |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/diesel fuel (high end of range) in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.6 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 4.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Petroleum Coke** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/heavy fuel oil (high end of range) in Bond et al (2004): Tables 9 & 10<br>d) Assume as for coal |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 4.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Combustion Other Industries_Excludes Brick Kilns\Non_specified petroleum products** | | | | |
| Nitrogen Oxides NOx | 513 ?b | Kilogramme | Terajoule | Assume as for Gas Diesel<br><br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.2, Table 3-4)<br>c) Assuming BC/OC ratio as for industry/diesel fuel (high end of range) in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 20 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 20 ?b | Kilogramme | Terajoule | |
| Black Carbon | 11.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.6 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Combustion Other Industries_Excludes Brick Kilns\Primary solid biomass** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | Primary solid biomass = wood, vegetal materials/wastes, animal prodcuts/wastes, and charcoal<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-5)<br>c) Assuming all PM2.5 is either BC or OC |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 143 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 140 ?b | Kilogramme | Terajoule | |
| Black Carbon | 39.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 72 ?c | Kilogramme | Terajoule | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |
| **Combustion Other Industries_Excludes Brick Kilns\Industrial waste** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>Assume the rest are the same as for Primary solid biomass:<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.2, Table 3-5)<br>c) Assuming all PM2.5 is either BC or OC |
| Sulfur Dioxide | 11 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{10}$ | 143 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 140 ?b | Kilogramme | Terajoule | |

| Demand\Manufacturing and Construction | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Black Carbon | 39.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 72 ?c | Kilogramme | Terajoule | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |

**Table S27:** Services emission factors use in LEAP-IBC analysis

| Demand\Services | Emission Factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Services\Other Bituminous Coal and Anthracite** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors (1.A.4 Small combustion, Table 3.7)<br>c) Assuming BC/OC ratio for industry/hard coal (upper end of range) in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 117 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 108 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.9 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 5.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Terajoule | |
| **Services\Coke Oven Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.8)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Services\Gas Works Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.8) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |

| Demand\Services | Emission Factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Services\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.8)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Services\LPG Liquefied Petroleum gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.8)<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Services\Motor Gasoline** | | | | |

| Demand\Services | Emission Factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Nitrogen Oxides NOx | 306 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for commercial/institutional (1.A.4 Small combustion, Table 3.9)<br>c) Assume OC = BC/3.5 (Bond et al., 2004 Tables 9 and 10)<br>d) Assume as for industry |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 21 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 18 ?b | Kilogramme | Terajoule | |
| Black Carbon | 10.1 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 2.89 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Services\Kerosene** | | | | |
| Nitrogen Oxides NOx | 306 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for commercial/institutional (1.A.4 Small combustion, Table 3.9)<br>c) Assume OC = BC/3.5 (Bond et al., 2004 Tables 9 and 10) d) Assume = gasoline |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 21 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 18 ?b | Kilogramme | Terajoule | |
| Black Carbon | 10.1 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 2.89 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Services\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 942 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 2 emission factors for reciprocating engines (Table 3-31)<br>c) From Klimont et al (2016) (Table S3.1) GAINS emission factors for diesel generators (no control)<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 96 ?c | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 96 ?c | Kilogramme | Terajoule | |
| Black Carbon | 40 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 28 ?c | Kilogramme | Terajoule | |

| Demand\Services | Emission Factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Services\Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 306 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor (1.A.4 Small combustion, Table 3.9)<br>c) Assuming BC/OC ratio as for industry/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 21 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 18 ?b | Kilogramme | Terajoule | |
| Black Carbon | 10.1 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.8 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Services\Non_specified petroleum products** | | | | |
| Nitrogen Oxides NOx | 942 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 2 emission factors for reciprocating engines (Table 3-31)<br>c) From Klimont et al (2016) (Table S3.1) GAINS emission factors for diesel generators (no control)<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 96 ?c | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 96 ?c | Kilogramme | Terajoule | |
| Black Carbon | 40 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 28 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Services\Primary solid biomass** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | **Primary solid biomass = wood, vegetal materials/wastes, animal prodcuts/wastes, and charcoal**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion (1.A.4 Small combustion, Table 3.10)<br>c) Assuming all PM2.5 is either BC or OC |
| Sulfur Dioxide | 11 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{10}$ | 143 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 140 ?b | Kilogramme | Terajoule | |

| Demand\Services | Emission Factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Black Carbon | 39.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 72 ?c | Kilogramme | Terajoule | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |

**Table S28:** Agriculture, Forestry and Fishing emission factors use in LEAP-IBC analysis

| Demand\Agriculture Forestry and Fishing | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Other Bituminous Coal and Anthracite** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2013) Tier 1 emission factors<br>c) Assuming BC/OC ratio for industry/hard coal (upper end of range) in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 117 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 108 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.9 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 5.2 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Coke Oven Coke** | | | | |
| Nitrogen Oxides NOx | 173 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2013) Tier 1 emission factors for combustion<br>c) Assuming BC/OC ratio as in Bond et al (2004) Tables 9 and 10 - for Industry<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 117 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 108 ?b | Kilogramme | Terajoule | |
| Black Carbon | 6.91 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 11.1 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Natural Gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | |

| Demand\Agriculture Forestry and Fishing | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2013) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.01 ?d | Kilogramme | Metric Tonne | |
| **LPG Liquefied Petroleum gas** | | | | |
| Nitrogen Oxides NOx | 74 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2013) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for natural gas in Bond et al (2004): Table 5<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.78 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.03 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.26 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.01 ?d | Kilogramme | Metric Tonne | |
| **Motor Gasoline** | | | | |
| Nitrogen Oxides NOx | 306 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for commercial/institutional<br>c) Assume OC = BC/3.5 (Bond et al., 2004 Tables 9 and 10)<br>d) Assume as for industry |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 21 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 18 ?b | Kilogramme | Terajoule | |
| Black Carbon | 10.1 ?b | Kilogramme | Terajoule | |

| Demand\Agriculture Forestry and Fishing | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Organic Carbon | 2.89 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Kerosene** | | | | |
| Nitrogen Oxides NOx | 306 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for commercial/institutional<br>c) Assume OC = BC/3.5 (Bond et al., 2004 Tables 9 and 10) d) Assume = gasoline |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 21 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 18 ?b | Kilogramme | Terajoule | |
| Black Carbon | 10.1 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 2.89 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 942 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 2 emission factors for reciprocating engines (Table 3-31)<br>c) From Klimont et al (2017) (Table S3.1) GAINS emission factors for diesel generators (no control)<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 96 ?c | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 96 ?c | Kilogramme | Terajoule | |
| Black Carbon | 40 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 28 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 306 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for industry/heavy fuel oil in Bond et al |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |

| Demand\Agriculture Forestry and Fishing | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{10}$ | 21 ?b | Kilogramme | Terajoule | (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Particulates $PM_{2.5}$ | 18 ?b | Kilogramme | Terajoule | |
| Black Carbon | 10.1 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 3.8 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Non_specified petroleum products** | | | | |
| Nitrogen Oxides NOx | 942 ?b | Kilogramme | Terajoule | **Assume as for gas diesel**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 2 emission factors for reciprocating engines (Table 3-31)<br>c) From Klimont et al (2017) (Table S3.1) GAINS emission factors for diesel generators (no control)<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 96 ?c | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 96 ?c | Kilogramme | Terajoule | |
| Black Carbon | 40 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 28 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.007 ?d | Kilogramme | Metric Tonne | |
| **Primary solid biomass** | | | | |
| Nitrogen Oxides NOx | 91 ?b | Kilogramme | Terajoule | **Primary solid biomass = wood, vegetal materials/wastes, animal prodcuts/wastes, and charcoal**<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2013) Tier 1 emission factors for combustion<br>c) Assuming all PM2.5 is either BC or OC |
| Sulfur Dioxide | 11 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{10}$ | 143 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 140 ?b | Kilogramme | Terajoule | |
| Black Carbon | 39.2 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 72 ?c | Kilogramme | Terajoule | |
| Ammonia | 37 ?b | Kilogramme | Terajoule | |

**Table S29:** Energy Industry - Own Use emission factors use in LEAP-IBC analysis

| Demand\Energy Industry Own Use | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Petroleum Refining\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 63*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 2 emission factors (1.A.1, Table 4-6)<br>c) Assume OC:BC ratio as indicated by Bond et al 2004 (Table 5) for natural gas<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.077 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.64 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Petroleum Refining\Crude oil** | | | | |
| Nitrogen Oxides NOx | 142*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for Heavy Fuel Oil (1.A.1, Table 4-4)<br>c) Values for Heavy Fuel Oil from Bond et al (2004): Tables 9 & 10<br>d) Assume as for Heavy Fuel Oil |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 15 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 9.0 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.504 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 0.19 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Petroleum Refining\Refinery gas** | | | | |
| Nitrogen Oxides NOx | 63*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors (1.A.1, Table 4-2)<br>c) Assume OC fraction is 0.5 of fine PM as indicated by Bond et al 2004 (Table 5) for natural gas<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.164 ?b | Kilogramme | Terajoule | |

| Demand\Energy Industry Own Use | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Organic Carbon | 0.44 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Petroleum Refining\LPG Liquefied Petroleum gas** | | | | |
| Nitrogen Oxides NOx | 89*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors<br>c) Assume OC factor is 8.3 x BC (derived from EMEP/EEA (2016) Tier 1) as indicated by Bond et al 2004 (Tables 5) for natural gas<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.022 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.19 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Petroleum Refining\Motor gasoline** | | | | |
| Nitrogen Oxides NOx | 65*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for industry/gasoline in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.8 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.268 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.077 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Petroleum Refining\Kerosene** | | | | |
| Nitrogen Oxides NOx | 65*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for industry/kerosene in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.8 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.268 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.077 ?c | Kilogramme | Terajoule | |

| Demand\Energy Industry Own Use | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Petroleum Refining\Gas diesel** | | | | |
| Nitrogen Oxides NOx | 65*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 2 emission factor<br>c) Assuming BC/OC ratio as for industry/diesel fuel in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.23 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.81 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.271 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.090 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Petroleum Refining\Heavy fuel oil** | | | | |
| Nitrogen Oxides NOx | 142*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 2 emission factor<br>c) Assuming BC/OC ratio as for Power/Heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 15*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 9.0*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.50*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.19*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Petroleum Refining\Petroleum coke** | | | | |
| Nitrogen Oxides NOx | 142*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for Power/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 25.2*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 19.3*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 1.08*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.41*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |

| Demand\Energy Industry Own Use | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Petroleum Refining\Non-specified and other petroleum products** | | | | |
| Nitrogen Oxides NOx | 142*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | Assume as for Heavy Fuel Oil<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for Power/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 25.2*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 19.3*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 1.08*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.41*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Terajoule | |
| **Other Own use_Excludes Charcoal Kilns** | | | | |
| **Other Own use_Excludes Charcoal Kilns\All Coal and Coke** | | | | |
| Nitrogen Oxides NOx | 21*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion<br>c) Derived from Bond et al (2004; Table 5) assuming 95%:5% ratio of captured versus uncaptured technology as for India in the mid 1990s (Bond et al, 2004: Table 8).<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | 91 ?b | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 79*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 55*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.54*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 0.39*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Coke oven gas** | | | | |
| Nitrogen Oxides NOx | 89*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors<br>c) Assume OC factor is 10 fold higher value than BC (derived from EMEP/EEA (2016) Tier 1) as indicated by Bond et al 2004 (Table 5) for natural gas<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.0223 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.223 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Blast Furnace Gas** | | | | |
| Nitrogen Oxides NOx | 89*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |

| Demand\Energy Industry Own Use | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors<br>c) Assume OC factor is 10 fold higher value than BC (derived from EMEP/EEA (2016) Tier 1) as indicated by Bond et al 2004 (Table 5) for natural gas<br>d) Assume = factor for natural gas |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.0223 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.223 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 89*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors<br>c) Assume OC factor is 10 fold higher value than BC (derived from EMEP/EEA (2016) Tier 1) as indicated by Bond et al 2004 (Table 5)<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.0223 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.223 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Crude Oil** | | | | |
| Nitrogen Oxides NOx | 142*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factor for Heavy Fuel Oil<br>c) Assuming BC/OC ratio as for Power/Heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Assume as for Heavy Fuel Oil |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 25.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 19.3 ?b | Kilogramme | Terajoule | |
| Black Carbon | 1.08 ?c | Kilogramme | Terajoule | |
| Organic Carbon | 0.40 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Refinery gas** | | | | |
| Nitrogen Oxides NOx | 89*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |

| Demand\Energy Industry Own Use | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors<br>c) Assume OC factor is 10 fold higher value than BC (derived from EMEP/EEA (2016) Tier 1) as indicated by Bond et al 2004 (Table 5) for natural gas<br>d) Assume = factor for natural gas |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.0223 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.223 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\LPG Liquefied Petroleum Gas** | | | | |
| Nitrogen Oxides NOx | 89*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors<br>c) Assume OC factor is 10 fold higher value than BC (derived from EMEP/EEA (2016) Tier 1) as indicated by Bond et al 2004 (Table 5) for natural gas<br>d) Assume = factor for natural gas |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.0223 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.223 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Motor Gasoline** | | | | |
| Nitrogen Oxides NOx | 65*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for industry/gasoline in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.8 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.268 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.077 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Kerosene** | | | | |
| Nitrogen Oxides NOx | 65*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |

| Demand\Energy Industry Own Use | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for industry/gasoline in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Particulates $PM_{10}$ | 3.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.8 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.268 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.077 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Gas Diesel Oil** | | | | |
| Nitrogen Oxides NOx | 65*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for industry/gasoline in Bond et al (2004): Tables 9 & 10<br>d) EMEP/Corinair (1996) |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.8 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.268 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.077 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.005 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 142*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for Power/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 25.2*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 19.3*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 1.08*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.41*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Petroleum Coke** | | | | |
| Nitrogen Oxides NOx | 142*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |

| Demand\Energy Industry Own Use | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for Power/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Particulates $PM_{10}$ | 25.2*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 19.3*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 1.08*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.41*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Terajoule | |
| **Other Own use_Excludes Charcoal Kilns\Non_specified petroleum products** | | | | |
| Nitrogen Oxides NOx | 142*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | Assume as for Heavy Fuel Oil<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factor<br>c) Assuming BC/OC ratio as for Power/heavy fuel oil in Bond et al (2004): Tables 9 & 10<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(SO2/S) * ((100 - Em Control)/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 25.2*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 19.3*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 1.08*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.41*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Other Own use_Excludes Charcoal Kilns\Primary Solid Biomass** | | | | |
| Nitrogen Oxides NOx | 81*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | Primary solid biomass = wood, vegetal materials/wastes, animal prodcuts/wastes, and charcoal<br>a) IPCC 2006 Guidelines - Tier 1 default EFs<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion<br>c) Assuming BC/OC ratio as for Power/Wood in Bond et al (2004): Tables 9 & 10<br>d) Not known - emission factor needed |
| Sulfur Dioxide | 11 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{10}$ | 155*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 133*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 4.4*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 18*(100 - Em Control)/100 ?c | Kilogramme | Terajoule | |
| Ammonia | 0 ?d | Kilogramme | Terajoule | |

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# II. Energy Transformation Sector

**Table S30:** Transformation emission factors use in LEAP-IBC analysis

| Transformation | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Transformation\Electricity Generation\Processes** | | | | |
| **Electricity generation\Other Bituminous Coal and Anthracite** | | | | |
| Nitrogen Oxides NOx | 209*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs (Vol 2, Table 2.2)<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors (1.A.1, Table 3-2)<br>c) Bond et al. (2004), Tables 9 & 10 from which central values are used for the technology/emission control mix for India in the mid 1990s (i.e. if a range is given by Bond et al., then upper value taken)<br>d) Battye et al. (1994) defaults (no NOx controls) |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 7.7* (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 3.4* (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.009*(100 - Em Control)/100 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.001* (100 - Em Control)/100 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Electricity generation\Sub Bituminous Coal** | | | | |
| Nitrogen Oxides NOx | 247*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs (Vol 2, Table 2.2)<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors (1.A.1, Table 3-3)<br>c) Bond et al. (2004), Tables 9 & 10 from which central values are used for the technology/emission control mix for India in the mid 1990s (i.e. if a range is given by Bond et al., then upper value taken)<br>d) Battye et al. (1994) defaults (no NOx controls) |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 7.9* (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 3.2* (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.002*(100 - Em Control)/100 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.004* (100 - Em Control)/100 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Electricity generation\Lignite** | | | | |
| Nitrogen Oxides NOx | 247*(100 - Em Control)/100 ?b | Kilogramme | Terajoule | |

| Transformation | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | a) IPCC 2006 Guidelines - Tier 1 default EFs (Vol 2, Table 2.2)<br>b) Derived from EMEP/EEA (2016) Tier 1 emission factors (1.A.1, Table 3-3)<br>c) Bond et al. (2004), Tables 9 & 10 from which central values are used for the technology/emission control mix for India in the mid 1990s (i.e. if a range is given by Bond et al., then upper value taken)<br>d) Battye et al. (1994) defaults (no NOx controls) |
| Particulates $PM_{10}$ | 7.9* (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 3.2* (100 - Em Control)/100 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.002*(100 - Em Control)/100 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.004* (100 - Em Control)/100 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.00028 ?d | Kilogramme | Metric Tonne | |
| **Electricity Generation\Natural Gas** | | | | |
| Nitrogen Oxides NOx | 89 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs (Vol 2, Table 2.2)<br>b) EMEP/EEA (2016) Tier 1 emission factors (1.A.1, Table 3-4)<br>c) Assume OC factor is 10 fold higher value than BC (derived from EMEP/EEA (2016) Tier 1) as indicated by Bond et al 2004 (Table 5)<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.89 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.0223 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.223 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.067 ?d | Kilogramme | Metric Tonne | |
| **Electricity Generation\Heavy Fuel Oil** | | | | |
| Nitrogen Oxides NOx | 142 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs (Vol 2, Table 2.2)<br>b) EMEP/EEA (2016) Tier 1 emission factors for combustion in 'Public Electricity and heat production' (1.A.1, Table 3-5)<br>c) Bond et al. (2004), Tables 9 & 10 from which central values are used for the technology/emission control mix for India in the mid 1990s (i.e. if a range is given by Bond et al., then upper value taken)<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 25.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 19.3 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.04 ?c | Kilogramme | Metric Tonne | |

| Transformation | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Organic Carbon | 0.015 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Electricity Generation\Diesel** | | | | |
| Nitrogen Oxides NOx | 65 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs (Vol 2, Table 2.2)<br>b) EMEP/EEA (2016) Tier 1 emission factors (1.A.1, Table 3-6)<br>c) Assume OC = BC/3.33 (Bond et al., 2004 Table 5, OC:BC ratio for Middle dist oil in industry/power)<br>d) Battye et al. (1994) defaults (no NOx controls). |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 3.2 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 0.8 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.268 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 0.0035 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.101 ?d | Kilogramme | Metric Tonne | |
| **Electricity Generation\Wood** | | | | |
| Nitrogen Oxides NOx | 81 ?b | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default Efs (Vol 2, Table 2.2)<br>b) EMEP/EEA (2016) Tier 1 emission factors (1.A.1, Table 3-7)<br>c) Assume OC factor is 4 fold higher value than BC as indicated by Bond et al 2004 (Tables 9 and 10)<br>d) US-EPA (2004) Emission Inventory Improvement Program: Estimating Ammonia Emissions from Anthropogenic<br>Non-agricultural Sources - Draft Final Report, Table III-1, page32. |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 155 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 133 ?b | Kilogramme | Terajoule | |
| Black Carbon | 4.4 ?b | Kilogramme | Terajoule | |
| Organic Carbon | 17.6 ?c | Kilogramme | Terajoule | |
| Ammonia | 0.043 ?d | Kilogramme | Terajoule | |
| **Electricity Generation\Industrial Waste** | | | | |
| Nitrogen Oxides NOx | 81 ?a | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs (Vol 2, Table 2.2)<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factors for biomass combustion in Public Electricity and Heat Production. (1.A.1, Table 3-7) |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |

| Transformation | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| Particulates $PM_{10}$ | 155 ?b | Kilogramme | Terajoule | c) Bond et al 2004 BC and OC values for Waste (Tables 9 and 10)<br>d) Assume as for wood waste. US-EPA (2004) Emission Inventory Improvement Program: Estimating Ammonia Emissions from Anthropogenic Non-agricultural Sources - Draft Final Report, Table III-1, page32.. |
| Particulates $PM_{2.5}$ | 133 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.013 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.002 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.043 ?d | Kilogramme | Terajoule | |
| **Electricity Generation\Municipal Waste** | | | | |
| Nitrogen Oxides NOx | 81 ?a | Kilogramme | Terajoule | a) IPCC 2006 Guidelines - Tier 1 default EFs (Vol 2, Table 2.2)<br>b) Assume = EMEP/EEA (2016) Tier 1 emission factors for biomass combustion in Public Electricity and Heat Production. (1.A.1, Table 3-7)<br>c) Bond et al 2004 BC and OC values for Waste (Tables 9 and 10)<br>d) US-EPA (2004) Emission Inventory Improvement Program: Estimating Ammonia Emissions from Anthropogenic Non-agricultural Sources - Draft Final Report, Table III-1, page32... |
| Sulfur Dioxide | SulfurContent*(1-SulfurRetention)*(SO2/S) * ((100 - Em Control[%])/100) | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 155 ?b | Kilogramme | Terajoule | |
| Particulates $PM_{2.5}$ | 133 ?b | Kilogramme | Terajoule | |
| Black Carbon | 0.013 ?c | Kilogramme | Metric Tonne | |
| Organic Carbon | 0.002 ?c | Kilogramme | Metric Tonne | |
| Ammonia | 0.6 ?d | Kilogramme | Terajoule | |
| **Transformation\Traditional Charcoal Making\Wood** | | | | |
| Nitrogen Oxides NOx | 0.18 ?a | Kilogramme | Metric Tonne | All factors are on a per tonne of wood feedstock basis<br>a) Bertschi et al. (2003) Table 3, For earthen charcoal-making kilns (in Zambia).<br>b) Bond et al (2004) Section 5.6.5 Charcoal: para 144<br>c) Assume 100% of S is retained in the charcoal (1 kg wood makes 0.28 kg charcoal, Bertschi et al (2003)) and wood at 0.015% S produces charcoal at 0.06% S (Smith et al 2000) |
| Sulfur Dioxide | 0 ?c | Kilogramme | Kilogramme | |
| Particulates $PM_{10}$ | 2.6 ?b | Kilogramme | Metric Tonne | |
| Particulates $PM_{2.5}$ | 2.6 ?b | Kilogramme | Metric Tonne | |
| Black Carbon | 0.19 ?b | Kilogramme | Metric Tonne | |
| Organic Carbon | 1.29 ?b | Kilogramme | Metric Tonne | |
| Ammonia | 0.37 ?a | Kilogramme | Metric Tonne | |

**Table S31:** Fugitive emission factors use in LEAP-IBC analysis

| Non-energy\Fugitives | Emission factor | Units | Per... | Reference source and assumptions |
|---|---|---|---|---|
| **Coke production** | | | | |
| **Traditional (uncontrolled) oven** | | | | |
| Sulfur Dioxide | 0.0035 ?a | Kilogramme | Metric Tonne Coke | a) EMEP/EEA (2016) Tier 1 defaults for 'Solid fuel transformation' (Uncontrolled = upper end of range) (1.B.1.b, Fugitive emissions from solid fuels. Table 3-1)<br>b) EFs are from Bond et al. (2004) Table 5 - then adjusted assuming 1 tonne coal makes 0.7 tonnes coke. (Assume Bond et al 'Uncaptured' = Uncontrolled conventional oven.)<br>c) IPCC 2006 Tier 1 default for coke production (Vol 3, Table 4.1) |
| Nitrogen Oxides $NO_x$ | 0.0046 ?a | Kilogramme | Metric Tonne Coke | |
| Ammonia | 0.01 ?a | Kilogramme | Metric Tonne Coke | |
| Particulates $PM_{10}$ | 29 ?b | Kilogramme | Metric Tonne Coke | |
| Particulates $PM_{2.5}$ | 15 ?b | Kilogramme | Metric Tonne Coke | |
| Black Carbon | 6.9 ?b | Kilogramme | Metric Tonne Coke | |
| Organic Carbon | 4.9?b | Kilogramme | Metric Tonne Coke | |
| **Improved (controlled) oven** | | | | |
| Sulfur Dioxide | 0.0008 ?a | Kilogramme | Metric Tonne Coke | a) EMEP/EEA (2016) Tier 1 defaults for 'Solid fuel transformation' for Controlled oven: default value (geometric mean)) (1.B.1.b, Fugitive emissions from solid fuels. Table 3-1)<br>b) EFs are from Bond et al. (2004) - then adjusted assuming 1 tonne coal makes 0.7 tonnes coke.<br>c) IPCC 2006 Tier 1 default for coke production (Vol 3, Table 4.1) |
| Nitrogen Oxides $NO_x$ | 0.0009 ?a | Kilogramme | Metric Tonne Coke | |
| Ammonia | 0.0037 ?a | Kilogramme | Metric Tonne Coke | |
| Particulates $PM_{10}$ | 5.6 ?b | Kilogramme | Metric Tonne Coke | |
| Particulates $PM_{2.5}$ | 1.9 ?b | Kilogramme | Metric Tonne Coke | |
| Black Carbon | 0.93 ?b | Kilogramme | Metric Tonne Coke | |
| Organic Carbon | 0.66?b | Kilogramme | Metric Tonne Coke | |
| **Oil Refining Processes** | | | | |
| Sulfur Dioxide | 0.62?a | Kilogramme | Tonne crude oil | a) EMEP/EEA (2016) Tier 1 defaults for 'Fugitive emissions oil: Rfining/storgae' (1.B.2.a.iv, Refining, storage, Table 3-1)<br>b) IPCC (2019) Refinement Tier 1 default (Table 4.2.4C (NEW)). Converted from original units assuming a crude oil densisty of 874 kg/m3. |
| Nitrogen Oxides | 0.24?a | Kilogramme | Tonne crude oil | |

**References:**

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Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Schöpp, W. (2017). Global anthropogenic emissions of particulate matter including black carbon. Atmospheric Chemistry and Physics Discussions, 17, pp 8681-8723.

# III. Non-Energy sector

**Table S32:** Forest and Grassland burning emission factors use in LEAP-IBC analysis

| Non Energy\On Site Burning of Forests and Grassland | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| **Secondary Tropical and Subtropical Forest** | | | |
| Biomass Consumed | 42 ?ab | Tonnes/hectare | a) All biomass is expressed on a dry weight basis.<br>b) IPCC (2006) default values (Vol 4, Chapter 2, Table 2.4). Use locally relevant factors if possible e.g from FAO State of the World's Forests (2009) ftp://ftp.fao.org/docrep/fao/011/i0350e/i0350e04c.pdf.<br>c) For Calluna heath, use 11.5; for sagebrush use 5.7 and for Fynbos use 12.9 t/ha<br>d) The amount of carbon released as CO relative to the total amount of carbon released due to burning.<br>e) Factor to convert to full molecular weight<br>f) The amount of nitrogen released as NOx relative to the total amount of nitrogen released due to burning.<br>g) Assume = TSP value from Andreae and Merlet (2001)<br>h) Assume equal to default for grassland<br>i) From Andreae and Merlet (2001) unless otherwise stated<br>j) Assume = factor for 'Savanna and grassland' category of Andreae and Merlet (2001)<br>h) Annual area burnt for forests: see FAO State of the worlds forests 2009 (http://www.fao.org/docrep/011/i0350e/i0350e00.htm) Annex 2: Table 2. Assume total forest area burnt = Mean annual forest cover change (if negative in sign). Also, Annex 2:Table 3 gives biomass before burning (tonnes/ha) by country. If this value is to be chosen then it must then be multiplied by the combustion factor (i.e. proportion of prefire fuel biomass consumed) for which IPCC (2006) default values are 0.36 for primary tropical forest, 0.55 for secondary tropical forest, 0.63 for Eucalyptus forest 0.45 for temperate forest and 0.59 for boreal forest. For example, if the biomass value in Annex 2:Table 3 is 179 tonnes/ha (and the forest is primary tropical), the actual amount burnt (i.e. 'Biomass consumption' to go in column B in this worksheet) will be 179 x 0.36 = 64.4 tonnes/ha. |
| Sulfur Dioxide | 0.57 ?i | kg/tonne biomass consumed | |
| Nitrogen Oxides | 2.45 ?i | kg/tonne biomass consumed | |
| Particulates $PM_{10}$ | 10.5 ?g | kg/tonne biomass consumed | |
| Particulates $PM_{2.5}$ | 9.1 ?i | kg/tonne biomass consumed | |
| Ammonia | 1.3 ?i | kg/tonne biomass consumed | |
| Black Carbon | 0.66 ?i | kg/tonne biomass consumed | |
| Organic Carbon | 5.2 ?i | kg/tonne biomass consumed | |
| **Tropical Subtropical Grasslands Ex Savanna Burn** | | | |
| Biomass Consumed | 5.2 ?ab | Tonnes/hectare | a) All biomass is expressed on a dry weight basis.<br>b) IPCC (2006) default values (Vol 4, Chapter 2, Table 2.4). Use locally relevant factors if possible e.g from FAO State of the World's Forests (2009) ftp://ftp.fao.org/docrep/fao/011/i0350e/i0350e04c.pdf.<br>c) For Calluna heath, use 11.5; for sagebrush use 5.7 and for Fynbos use 12.9 t/ha<br>d) The amount of carbon released as CO relative to the total amount of carbon released due to burning.<br>e) Factor to convert to full molecular weight<br>f) The amount of nitrogen released as NOx relative to the total amount of nitrogen released due to burning.<br>g) Assume = TSP value from Andreae and Merlet (2001)<br>h) Assume equal to default for grassland<br>i) From Andreae and Merlet (2001) unless otherwise stated<br>j) Assume = factor for 'Savanna and grassland' category of Andreae and Merlet (2001)<br>h) Annual area burnt for forests: see FAO State of the worlds forests 2009 |
| Sulfur Dioxide | 0.35 ?i | kg/tonne biomass consumed | |
| Nitrogen Oxides | 6 ?i | kg/tonne biomass consumed | |
| Particulates $PM_{10}$ | 8.3 ?g | kg/tonne biomass consumed | |
| Particulates $PM_{2.5}$ | 5.4 ?i | kg/tonne biomass consumed | |
| Ammonia | 1.05 ?j | kg/tonne biomass consumed | |
| Black Carbon | 0.48 ?j | kg/tonne biomass consumed | |
| Organic Carbon | 3.4 ?j | kg/tonne biomass consumed | |

| Non Energy\On Site Burning of Forests and Grassland | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| | | | (http://www.fao.org/docrep/011/i0350e/i0350e00.htm) Annex 2: Table 2. Assume total forest area burnt = Mean annual forest cover change (if negative in sign). Also, Annex 2:Table 3 gives biomass before burning (tonnes/ha) by country. If this value is to be chosen then it must then be multiplied by the combustion factor (i.e. proportion of prefire fuel biomass consumed) for which IPCC (2006) default values are 0.36 for primary tropical forest, 0.55 for secondary tropical forest, 0.63 for Eucalyptus forest 0.45 for temperate forest and 0.59 for boreal forest. For example, if the biomass value in Annex 2:Table 3 is 179 tonnes/ha (and the forest is primary tropical), the actual amount burnt (i.e. 'Biomass consumption' to go in column B in this worksheet) will be 179 x 0.36 = 64.4 tonnes/ha. |
| **General Shrubland** | | | |
| Biomass Consumed | 27 ?ac | Tonnes/hectare | a) All biomass is expressed on a dry weight basis.<br>b) IPCC (2006) default values (Vol 4, Chapter 2, Table 2.4). Use locally relevant factors if possible e.g from FAO State of the World's Forests (2009) ftp://ftp.fao.org/docrep/fao/011/i0350e/i0350e04c.pdf.<br>c) For Calluna heath, use 11.5; for sagebrush use 5.7 and for Fynbos use 12.9 t/ha<br>d) The amount of carbon released as CO relative to the total amount of carbon released due to burning.<br>e) Factor to convert to full molecular weight<br>f) The amount of nitrogen released as NOx relative to the total amount of nitrogen released due to burning.<br>g) Assume = TSP value from Andreae and Merlet (2001)<br>h) Assume equal to default for grassland<br>i) From Andreae and Merlet (2001) unless otherwise stated<br>j) Assume = factor for 'Savanna and grassland' category of Andreae and Merlet (2001)<br>h) Annual area burnt for forests: see FAO State of the worlds forests 2009 (http://www.fao.org/docrep/011/i0350e/i0350e00.htm) Annex 2: Table 2. Assume total forest area burnt = Mean annual forest cover change (if negative in sign). Also, Annex 2:Table 3 gives biomass before burning (tonnes/ha) by country. If this value is to be chosen then it must then be multiplied by the combustion factor (i.e. proportion of prefire fuel biomass consumed) for which IPCC (2006) default values are 0.36 for primary tropical forest, 0.55 for secondary tropical forest, 0.63 for Eucalyptus forest 0.45 for temperate forest and 0.59 for boreal forest. For example, if the biomass value in Annex 2:Table 3 is 179 tonnes/ha (and the forest is primary tropical), the actual amount burnt (i.e. 'Biomass consumption' to go in column B in this worksheet) will be 179 x 0.36 = 64.4 tonnes/ha. |
| Sulfur Dioxide | 0.35 ?h | kg/tonne biomass consumed | |
| Nitrogen Oxides | 6 ?h | kg/tonne biomass consumed | |
| Particulates $PM_{10}$ | 8.3 ?h | kg/tonne biomass consumed | |
| Particulates $PM_{2.5}$ | 5.4 ?h | kg/tonne biomass consumed | |
| Ammonia | 0.26 ?j | kg/tonne biomass consumed | |
| Black Carbon | 0.48 ?j | kg/tonne biomass consumed | |
| Organic Carbon | 3.4 ?j | kg/tonne biomass consumed | |

**Table S33:** Livestock Enteric Fermentation and Manure Management emission factors use in LEAP-IBC analysis

| Non Energy\Agriculture\Livestock Enteric Fermentation and Manure Management | Emission factor | Units | Reference source and assumptions |
|---|---|---|---|
| All categories of animal | | | a) Tier 1 default emission factors from EMEP/EEA (2016) (Setion 3.B Manure management, Table 3.2)<br>b) IPCC manure management CH4 default for indian subcontinent assuming 26 °C annual average temp. For **other Asia** (>25 °C) use 28 for dairy cows, 1 for other cattle; 2 for buffalo and 6 for pigs; For **Africa** use 1 for dairy cows, other cattle and pigs; for **Middle East** , use 2 for dairy cows, 1 for other cattle and 5 for buffallo and pigs; for **L. America** use 1 for dairy cows, other cattle, buffallo and pigs. For other regions (**Europe, N. America, Oceana**) and countries with annual average temp < 26 °C, user should consult IPCC 2006 (Vol 4, Chapt 10,Tables 10.14 and 10.15) go to http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf |
| **Dairy Cattle** | | | |
| Ammonia from Manure Management | 28.7 ?a | kg/animal | a) Tier 1 default emission factors from EMEP/EEA (2016). NH3 emission factor for dairy cattle assume 'solid' rather than 'slurry' system (use 39.3 kg/animal for slurry). c) IPCC enteric fermentation CH4 default for cattle in the Indian subcontinent. For other Asia use 68 (dairy) and 47 (other cattle); For Africa and Middle East use 46 (dairy) and 31 (other cattle) and for L. America use 72 (dairy) and 56 (other cattle). For enteric fermentation EFs for cattle in other regions (Europe, N. America, Oceana) consult IPCC 2006 (Vol 4, Chapt 10, Table 10.11). http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf |
| **Other Cattle** | | | |
| Ammonia from Manure Management | 9.2 ?a | kg/animal | a) Tier 1 default emission factors from EMEP/EEA (2016). Factor for other cattle assume 'solid' rather than 'slurry' system (use 13.4 kg/animal for slurry).<br>c) IPCC enteric fermentation CH4 default for cattle in the Indian subcontinent. For other Asia use 68 (dairy) and 47 (other cattle); For Africa and Middle East use 46 (dairy) and 31 (other cattle) and for L. America use 72 (dairy) and 56 (other cattle). For enteric fermentation EFs for cattle in other regions (Europe, N. America, Oceana) consult IPCC 2006 (Vol 4, Chapt 10, Table 10.11). http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf |
| **Buffalo** | | | |
| Ammonia from Manure Management | 9.0 ?a | kg/animal | c) IPCC (2006) Tier 1 default values (Vol 4, Chapter 10, Table 10.10) |
| **Pigs** | | | |
| Ammonia from Manure Management | 6.5 ?a | kg/animal | c) IPCC (2006) Tier 1 default values for developing countries only (Vol 4, Chapter 10, Table 10.10). For developed countries use value 1.5 for pigs (swine). |
| **Sheep** | | | |
| Ammonia from Manure Management | 1.4 ?a | kg/animal | c) IPCC (2006) Tier 1 default values for developing countries only (Vol 4, Chapter 10, Table 10.10). For developed countries use value of 8 for sheep. |
| **Goats** | | | |
| Ammonia from Manure Management | 1.4 ?a | kg/animal | c) IPCC (2006) Tier 1 default values (Vol 4, Chapter 10, Table 10.10). |

| Non Energy\Agriculture\Livestock Enteric Fermentation and Manure Management | Emission factor | Units | Reference source and assumptions |
|---|---|---|---|
| **Horses** | | | |
| Ammonia from Manure Management | 14.8 ?a | kg/animal | c) IPCC (2006) Tier 1 default values (Vol 4, Chapter 10, Table 10.10). |
| **Mules and Asses** | | | |
| Ammonia from Manure Management | 14.8 ?a | kg/animal | c) IPCC (2006) Tier 1 default values (Vol 4, Chapter 10, Table 10.10) . |
| **Poultry** | | | |
| Ammonia from Manure Management | 0.48 ?a | kg/animal | a) Tier 1 default emission factors from EMEP/EEA (2016), (3.B Manure management, Table 3.2). Emission factor of 0.48 is for laying hens. Use 0.22 for chicken broilers, 0.95 for turkeys, 0.68 for ducks and 0.35 for geese. |
| **Fur animals** | | | |
| Ammonia from Manure Management | 0.02 ?a | kg/animal | |
| **Camels** | | | |
| Ammonia from Housing Management | 10.5 ?a | kg/animal | c) IPCC (2006) Tier 1 default values (Vol 4, Chapter 10, Table 10.10) . |

**Table S34:** Fertilizer application emission factors use in LEAP-IBC analysis

| Non Energy\Agriculture\ Fertilizer application | Emission factor | Units | Reference source and assumptions |
|---|---|---|---|
| **For all fertilizers listed below** | | | **Ammonia emission factors are EMEP/EEA (2016) Tier 2 defaults for temperate countries (annual temp 15-25 ºC)**: Section 3.D Crop production and agricultural soils, Table 3.2. For cool (< 15 ºC) or warm (>25 ºC) countries see alterantive values given in the same table.<br>- Nitrogen oxide emission factors (as NO) are derived EMEP/EEA (2016) Tier 1 defaults (as NO2) (3.D Crop production and agricultural soils, Table 3.2)<br>**- Fertilizer use must be in tonnes as nutrient (i.e. "as nitrogen (N)"):** National level data can be found from FAOSTAT (http://faostat3.fao.org/download/R/*/E): This link should take you to the 'Download data' section and the domain 'Inputs'. Select 'Fertilizers'. Select 'countries', 'items' (e.g. Ammonium sulphate, Ammonium nitrate) and 'element' ('Consumption' not 'Consumption in nutrients' which does not work!). Warning: as data they are not expressed as tonnes product, they must first be converted into "as nutrient N" by dividing by appropriate factor (e.g. 4.76 for ammonium sulphate, 2.99 ammonium nitrate, 3.70 calcium ammonium nitrate, 1.22 anhydrous ammonia, 2.17 for urea, 5.56 for di-ammonium phosphate, 5.00 for other complex NK, NPK fertilizers, 2.52 for nitrogen solutions). To get data before 2002 select 'Fertlizers archive' instead of 'Fertlizers' - data are expressed here "as N" so no need to convert.<br>**Indirect N2O emissions calculated as:**<br>0.01*Fertilizer Use[Tonnes/Year] *(Ammonia emission factor[kg/kg N]*14/17)+Fertilizer Use[Tonnes/Year] * (NO Emission factor[kg/kg N])*14/46)*44/14 [IPCC, 2006, Tier 1 default method] |
| **Ammonium Sulphate Low soil pH** | | | |
| Ammonia | 0.092 | kg/kg N | Normal soil pH = pH less than 7.0 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Ammonium Sulphate High soil pH** | | | |
| Ammonia | 0.17 | kg/kg N | High soil pH = pH greater than 7.0 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Ammonium Nitrate** | | | |
| Ammonia | 0.016 | kg/kg N | Value for normal soil pH (less than 7.0), for high pH use 0.033 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Calcium Ammonium Nitrate** | | | |
| Ammonia | 0.008 | kg/kg N | Value for normal soil pH (less than 7.0), for high pH use 0.017 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Anhydrous Ammonia** | | | |
| Ammonia | 0.02 | kg/kg N | Value for normal soil pH (less than 7.0), for high pH use 0.036 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Urea** | | | |
| Ammonia | 0.159 | kg/kg N | For normal soil pH (less than 7.0), for high pH use 0.168 |

| Non Energy\Agriculture\ Fertilizer application | Emission factor | Units | Reference source and assumptions |
|---|---|---|---|
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Combined Ammonium Phosphates Low soil pH** | | | |
| Ammonia | 0.051 | kg/kg N | Normal soil pH = pH less than 7.0 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Combined Ammonium Phosphates High soil pH** | | | |
| Ammonia | 0.094 | kg/kg N | High soil pH = pH greater than 7.0 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Ammonium Solutions** | | | |
| Ammonia | 0.1 | kg/kg N | Assume = EMEP/EEA catergory 'N solutions'. For normal soil pH (less than 7.0), for high pH use 0.097 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |
| **Other Complex NK and NPK Fertilizers** | | | |
| Ammonia | 0.067 | kg/kg N | Value for normal soil pH (less than 7.0), for high pH use 0.094 |
| | | | IPCC (2006) Tier 1 default (Vol 4, Table 11.1) |

**Table S35:** Crop residue burning emission factors use in LEAP-IBC analysis

| Non-energy\Agricultural Residue Burning | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| **Rice** | | | |
| Residue to Crop Ratio | 1.4 ?a | ratio | a) EMEP/EEA (2016) default values. Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016) (3.F Field burning of agricultural wastes, Table 3-6).<br>e) Value given by Andreae and Merlet (2001) for agricultural residues |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.4 ? d | kg/tonne residue burned | |
| Sulfur Dioxide | 0.3 ?d | kg/tonne residue burned | |
| Ammonia | 2.4 ?d | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.8 ?d | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.5 ?d | kg/tonne residue burned | |
| Black Carbon | 0.5 ?d | kg/tonne residue burned | |
| Organic Carbon | 3.3 ?e | kg/tonne residue burned | |
| **Wheat** | | | |
| Residue to Crop Ratio | 1.5 ?f | ratio | a) EMEP/EEA (2016) default values. Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016) (3.F Field burning of agricultural wastes, Table 3-3).<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991) |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?d | kg/tonne residue burned | |
| Sulfur Dioxide | 0.5 ?d | kg/tonne residue burned | |
| Ammonia | 2.4 ?d | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?d | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?d | kg/tonne residue burned | |
| Black Carbon | 0.5 ?d | kg/tonne residue burned | |
| Organic Carbon | 3.3 ?e | kg/tonne residue burned | |
| **Millet** | | | |
| Residue to Crop Ratio | 1.2 ?f | ratio | |

| Non-energy\Agricultural Residue Burning | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| Dry Matter Fraction | 85 ?a | % | a) EMEP/EEA (2016) default values . Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) (3.F Field burning of agricultural wastes, Table 3-1) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?c | kg/tonne residue burned | |
| Sulfur Dioxide | 0.48 ?h | kg/tonne residue burned | |
| Ammonia | 2.4 ?c | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?c | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?c | kg/tonne residue burned | |
| Black Carbon | 0.5 ?c | kg/tonne residue burned | |
| Organic Carbon | 3.3 ?e | kg/tonne residue burned | |
| **Soya** | | | |
| Residue to Crop Ratio | 2.1 ?a | ratio | a) EMEP/EEA (2016) default values (3.F Field burning of agricultural wastes, Table ). Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) (3.F Field burning of agricultural wastes, Table 3-1) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?c | kg/tonne residue burned | |
| Sulfur Dioxide | 0.48 ?h | kg/tonne residue burned | |
| Ammonia | 2.4 ?c | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?c | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?c | kg/tonne residue burned | |
| Black Carbon | 0.5 ?c | kg/tonne residue burned | |
| Organic Carbon | 3.3 ?e | kg/tonne residue burned | |
| **Maize** | | | |
| Residue to Crop Ratio | 0.33 ?f | ratio | a) EMEP/EEA (2016) default values (3.F Field burning of agricultural wastes, Table ). Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016) (section 3.F Field burning of agricultural wastes, Table 3-5)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 1.8 ? d | kg/tonne residue burned | |

| Non-energy\Agricultural Residue Burning | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| Sulfur Dioxide | 0.2 ?d | kg/tonne residue burned | f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Ammonia | 2.4 ?d | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 6.2 ?d | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 6.0 ?d | kg/tonne residue burned | |
| Black Carbon | 0.75 ?d | kg/tonne residue burned | |
| Organic Carbon | 3.3 ?e | kg/tonne residue burned | |
| **Jute** | | | |
| Residue to Crop Ratio | 2.15 ?f | ratio | a) EMEP/EEA (2016) default values (3.F Field burning of agricultural wastes, Table 3-1). Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) (3.F Field burning of agricultural wastes, Table 3-1) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?c | kg/tonne residue burned | |
| Sulfur Dioxide | 0.48 ?h | kg/tonne residue burned | |
| Ammonia | 2.4 ?c | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?c | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?c | kg/tonne residue burned | |
| Black Carbon | 0.5 ?c | kg/tonne residue burned | |
| Organic Carbon | 3.3 ?e | kg/tonne residue burned | |
| **Cotton** | | | |
| Residue to Crop Ratio | 3.0 ?f | ratio | a) EMEP/EEA (2016) default values (3.F Field burning of agricultural wastes, Table ). Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) (3.F Field burning of agricultural wastes, Table 3-1) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?c | kg/tonne residue burned | |
| Sulfur Dioxide | 0.48 ? h | kg/tonne residue burned | |
| Ammonia | 2.4 ?c | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?c | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?c | kg/tonne residue burned | |

| Non-energy\Agricultural Residue Burning | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| Black Carbon | 0.5 ?c | kg/tonne residue burned | |
| Organic Carbon | 3.3 ? e | kg/tonne residue burned | |
| **Groundnut** | | | |
| Residue to Crop Ratio | 2.0 ?f | ratio | a) EMEP/EEA (2016) default values (Section 3.F Field burning of agricultural wastes, Table ). Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) (Section 3.F Field burning of agricultural wastes, Table 3-1) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?c | kg/tonne residue burned | |
| Sulfur Dioxide | 0.48 ?h | kg/tonne residue burned | |
| Ammonia | 2.4 ?c | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?c | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?c | kg/tonne residue burned | |
| Black Carbon | 0.5 ?c | kg/tonne residue burned | |
| Organic Carbon | 3.3 ? e | kg/tonne residue burned | |
| **Sugarcane** | | | |
| Residue to Crop Ratio | 0.1 ?g | ratio | a) EMEP/EEA (2016) default values. Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) (Section 3.F Field burning of agricultural wastes, Table 3-1) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?c | kg/tonne residue burned | |
| Sulfur Dioxide | 0.48 ? h | kg/tonne residue burned | |
| Ammonia | 2.4 ?c | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?c | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?c | kg/tonne residue burned | |
| Black Carbon | 0.5 ?c | kg/tonne residue burned | |
| Organic Carbon | 3.3 ? e | kg/tonne residue burned | |
| **Rapeseed and Mustard** | | | |
| Residue to Crop Ratio | 1.8 ?g | ratio | |

| Non-energy\Agricultural Residue Burning | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| Dry Matter Fraction | 85 ?a | % | a) EMEP/EEA (2016) default values. Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) (Section 3.F Field burning of agricultural wastes, Table 3-1) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?c | kg/tonne residue burned | |
| Sulfur Dioxide | 0.48 ? h | kg/tonne residue burned | |
| Ammonia | 2.4 ?c | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?c | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?c | kg/tonne residue burned | |
| Black Carbon | 0.5 ?c | kg/tonne residue burned | |
| Organic Carbon | 3.3 ? e | kg/tonne residue burned | |
| **Other crop** | | | |
| Residue to Crop Ratio | 0 | ratio | a) EMEP/EEA (2016) default values. Use locally determined factors where available.<br>b) The average between 0% (none) and 100% (all) of the residue burned in the fields.<br>c) Tier 1 emision factor from EMEP/EEA (2016) (Section 3.F Field burning of agricultural wastes, Table 3-1) unless otherwise stated<br>d) Tier 2 emision factor from EMEP/EEA (2016)<br>e) Value given by Andreae and Merlet (2001) for agricultural residues<br>f) TIFAC (1991)<br>g) Tyagi (1989)<br>h) Reddy and Venkataraman (2002b) unless otherwise indicated |
| Dry Matter Fraction | 85 ?a | % | |
| Fraction Burned in Fields | 25 ?b | % | |
| Fraction Oxidized | 90 ?a | % | |
| Nitrogen Oxides | 2.3 ?c | kg/tonne residue burned | |
| Sulfur Dioxide | 0.48 ? h | kg/tonne residue burned | |
| Ammonia | 2.4 ?c | kg/tonne residue burned | |
| Particulates $PM_{10}$ | 5.7 ?c | kg/tonne residue burned | |
| Particulates $PM_{2.5}$ | 5.4 ?c | kg/tonne residue burned | |
| Black Carbon | 0.5 ?c | kg/tonne residue burned | |
| Organic Carbon | 3.3 ? e | kg/tonne residue burned | |

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**Table S36:** Waste incineration emission factors use in LEAP-IBC analysis

| Non-energy\Waste Incineration | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| **Municiple waste** | | | |
| **Modern waste incineration plant** | | | |
| Sulfur Dioxide | 0.087 ?a | kg/tonne waste | a) EMEP/EEA (2016) - Tier 1 default (5.C.1.a Municipal waste incineration, Table 3-1)<br>b) IPCC (2006) |
| Nitrogen Oxides | 1.07 ?a | kg/tonne waste | |
| Ammonia | 0.003 ?a | kg/tonne waste | |
| Particulates $PM_{10}$ | 0.003 ?a | kg/tonne waste | |
| Particulates $PM_{2.5}$ | 0.003 ?a | kg/tonne waste | |
| Black Carbon | 0.00011 ?a | kg/tonne waste | |
| Organic Carbon | 0 | kg/tonne waste | |
| **Uncontrolled waste incineration plant** | | | |
| Sulfur Dioxide | 1.7 ?a | kg/tonne waste | a) EMEP/EEA (2016) - Uncontrolled Tier 2 default (5.C.1.a Municipal waste incineration, Table 3-2)<br>b) IPCC (2006) |
| Nitrogen Oxides | 1.8 ?a | kg/tonne waste | |
| Ammonia | 0 | kg/tonne waste | |
| Particulates $PM_{10}$ | 13.7 ?a | kg/tonne waste | |
| Particulates $PM_{2.5}$ | 9.2 ?a | kg/tonne waste | |
| Black Carbon | 0.322 ?a | kg/tonne waste | |
| Organic Carbon | 0 | kg/tonne waste | |
| **Open Burning** | | | |
| Sulfur Dioxide | 0.5 ?a | kg/tonne waste | |

| Non-energy\Waste Incineration | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| Nitrogen Oxides | 4.9 ?b | kg/tonne waste | a) US EPA (1995)<br>b) Mean of $NO_2$ values from Yokelson et al (2011) [6.87] and US EPA (1995) [3.0]<br>c) Akagi et al (2011)<br>d) Akagi et al (2011) value for identified NMVOC (use 22.6 gk/t for identified plus unidentfied NMVOC).<br>e) Woodall et al (2012) |
| Ammonia | 1.12 ?c | kg/tonne waste | |
| Particulates $PM_{10}$ | 11.9 ?e | kg/tonne waste | |
| Particulates $PM_{2.5}$ | 9.8 ?c | kg/tonne waste | |
| Black Carbon | 0.65 ?c | kg/tonne waste | |
| Organic Carbon | 5.27 ?c | kg/tonne waste | |
| **Industrial waste** | | | |
| **Uncontrolled** | | | |
| Sulfur Dioxide | 1.25 ?a | kg/tonne waste | a) US EPA (1995) uncontrolled defaults for multiple chamber unless otherwise indicated<br>b) Expressed as methane<br>c) Factors for PM10 not given by US EPA (1995); For default assume = TSP factor<br>d) Assume same PM2.5/PM10 ratio as for Uncontrolled waste incineration plant<br>e) IPCC (2006), Vol 5, Chapter 5, Table 5.3: Assume uncontrolled = Batch type-stoker |
| Nitrogen Oxides | 1.5 ?a | kg/tonne waste | |
| Ammonia | 0 | kg/tonne waste | |
| Particulates $PM_{10}$ | 3.5 ?c | kg/tonne waste | |
| Particulates $PM_{2.5}$ | 2.8 ?d | kg/tonne waste | |
| Black Carbon | 0 | kg/tonne waste | |
| Organic Carbon | 0 | kg/tonne waste | |
| **Modern plant with emission controls** | | | |
| Sulfur Dioxide | 0.047 ?a | kg/tonne waste | a) EMEP/EEA (2016) - Tier 1 default<br>b) IPCC (2006), Vol 5, Chapter 5, Table 5.3: Assume Modern plant = Continuous-stoker<br>c) not known |
| Nitrogen Oxides | 0.87 ?a | kg/tonne waste | |
| Ammonia | 0 | kg/tonne waste | |
| Particulates $PM_{10}$ | 0.007 ?a | kg/tonne waste | |
| Particulates $PM_{2.5}$ | 0.004 ?a | kg/tonne waste | |

| Non-energy\Waste Incineration | Emission Factor | Units | Reference source and assumptions |
|---|---|---|---|
| Black Carbon | 0.00014 ?a | kg/tonne waste | |
| Organic Carbon | 0 ?c | kg/tonne waste | |

**Reference**


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