Asian and Pacific Centre for Transfer of Technology

Assessment Report

Technological Interventions and Gaps in Air Pollution Control in Bangkok, Thailand

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FOREWORD

It is with great pleasure that I introduce this document: *Technological Interventions and Gaps in Air Pollution Control in Bangkok, Thailand*.

The Asian and Pacific Centre for Transfer of Technology (APCTT) of the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), has long been dedicated to fostering innovation and facilitating the transfer of technology across our diverse member countries. APCTT's key mandate is to strengthen the technology transfer capabilities in the Asia- Pacific region and to facilitate exchange of new, emerging and environmentally sound technologies between the member countries.

This document was produced under the project "Enhanced capabilities to adopt innovative technologies for city air pollution control in select countries of the Asia Pacific" supported by the Korea ESCAP Cooperation Fund. The project objective was to support three ESCAP member States (Bangladesh, India and Thailand) to strengthen policies and city level action plans to facilitate adoption of innovative technologies for controlling air pollution. The project aimed to improve the availability of technical knowledge regarding innovative technologies, and good practices and enabling policies for air pollution control in three cities (Bangkok, Dhaka and Gurugram).

This assessment report examines the current state of air pollution technologies employed in Bangkok. It identifies the key technological needs and gaps that require urgent attention for controlling urban air pollution. As we attempt to enhance our understanding of the complexities of air pollution in key cities in Asia Pacific, the findings of this report will serve as a valuable resource for policymakers, city planners and practitioners. I hope that this report will play an important role in shaping the trajectory of air pollution control initiatives in Bangkok and other cities in Asia Pacific.

Preeti Soni
Head
Asian and Pacific Centre for Transfer of Technology
Economic and Social Commission for Asia and the Pacific

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This publication was prepared by Dr. Ekbordin Winijkul and Ms. Kanokwan Limsiriwong of the Environmental Engineering and Management Department of the Asian Institute of Technology, Bangkok under a consultancy assignment with ESCAP-APCTT. The contributions of the Thailand Institute of Scientific and Technological Research (TISTR), Pollution Control Department (PCD), Office of Transport and Traffic Policy and Planning (OTP), Bangkok Metropolitan Administration (BMA) and Thailand's Hub of Talents on Air Pollution and Climate (HTAPC) have been integral in enhancing the depth and relevance of the findings. The report benefited from comments and suggestions from Mr. Satyabrata Sahu and Mr. Pankaj Kumar Shrivastav from the ESCAP-APCTT.

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1. INTRODUCTION

Current air quality in Thailand

Thailand ranks in the middle among the countries in Southeast Asia in terms of annual $PM_{2.5}$ concentration. In the years 2021-2022, Thailand was the 5th country out of 10 in Southeast Asia, as shown in Figure 1 (IQAir, 2022; IQAir, 2021). However, the annual fine particulate matter was 23.8 µg/m³ in 2020, nearly 5 times higher than the World Health Organization (WHO) guideline (5 µg/m³, 2021 air quality guideline). At the current pollution levels, air pollution is shortening Thai residents' life expectancy by an average of 1.8 years relative to what it would be had the WHO guidelines been permanently met. This health burden of air pollution is highest in the provinces of Bangkok, Nakhon Ratchasima, and Chiang Mai (AQLI, 2022).

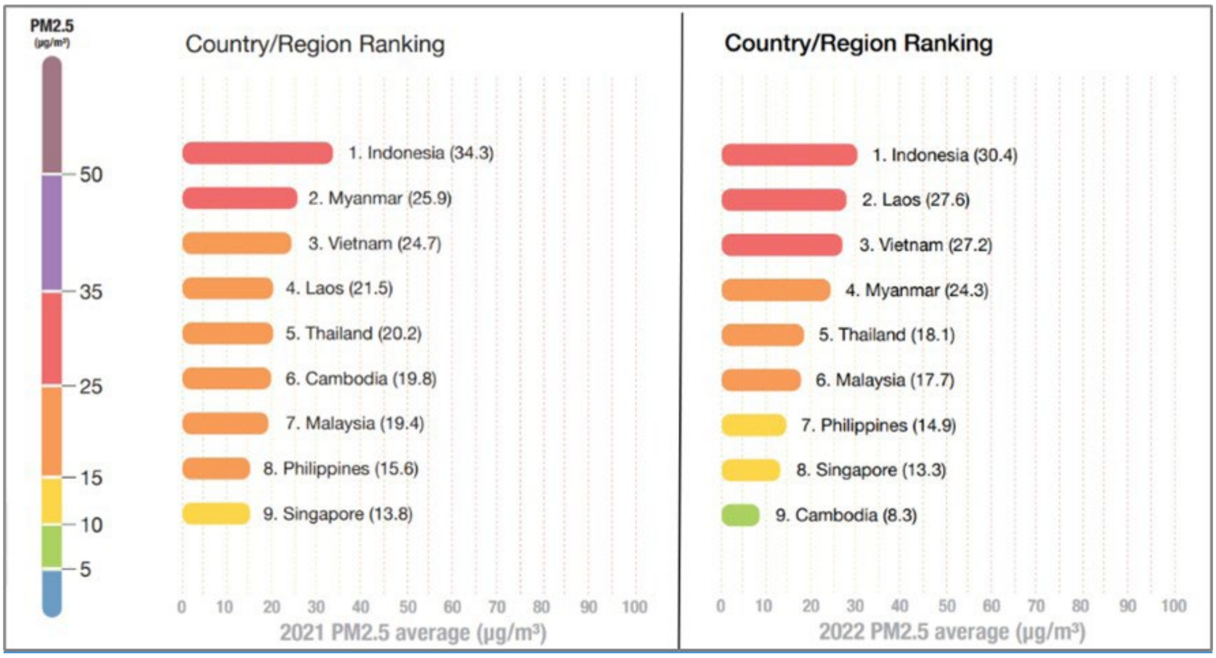

Figure 1: Ranking of annual $PM_{2.5}$ concentration in Southeast Asia (µg/m³) in 2021-2022 *(IQAir, 2022; IQAir, 2021)*

Based on statistical data compiled from air quality measurements reported by IQ Air, Thailand has experienced an improvement in air quality over the past 5 years, as shown in Figure 2. Moreover, in 2022, Thailand had decreased air pollution, with the annual average $PM_{2.5}$ concentration reduced to 18.1 µg/m³, a 10.4% decrease from 2021 levels as shown in Figure 3 (IQAir, 2022). This trend aligns with the report on the state of air pollution in Thailand in 2021 by the Thai Pollution Control Department (PCD, 2022), using only the official monitoring stations in Thailand (77 stations across 46 provinces). The 24-hour average $PM_{2.5}$ concentrations ranged from 29 to 414 micrograms per cubic meter (µg/m³), while the annual averages ranged from 10 to 40 µg/m³, with a national average of 22 µg/m³. The level reduced from the previous year by 4% (23 µg/m³ in 2020). The 10-year trends were decreasing steadily in all regions, as shown in Figure 4.

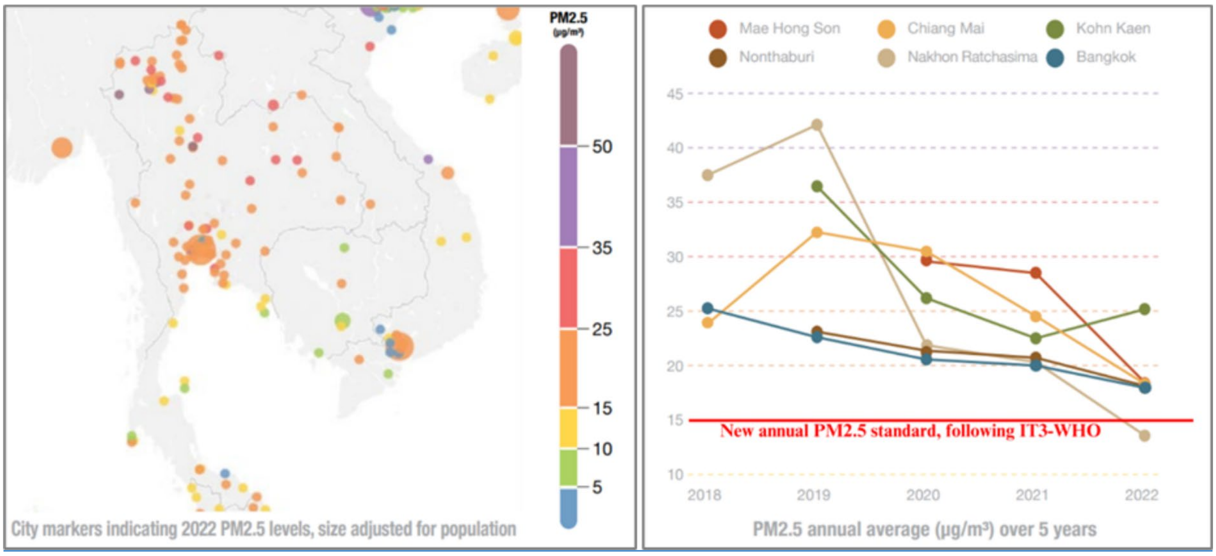

Figure 2: Annual average $PM_{2.5}$ (µg/m³) over 5 years *(IQAir, 2022)*

City	2022	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	2021
Bangkok	18.0	25.4	27.1	20.1	27.9	12.2	8.4	7.7	8.6	11.0	21.2	22.5	24.6	20.0
Chiang Mai	18.4	19.5	24.8	39.9	38.8	13.2	7.2	6.0	5.7	7.9	14.8	17.8	26.3	24.9
Khon Kaen	25.1	41.8	37.7	40.2	40.6	18.3	13.9	12.8	11.8	15.4	2.8	No Data		22.6
Mae Hong Son	18.8	No Data		73.2	55.6	17.5	10.4	5.0	5.4	9.4	15.3	16.1	26.3	28.5
Nakhon Ratchasima	13.9	21.9	24.2	27.5	21.3	6.8	5.7	8.3	7.0	8.0	12.3	10.1	13.7	20.3
Nonthaburi	18.0	25.7	29.6	20.9	31.2	11.6	6.5	6.3	7.3	9.7	21.4	22.9	23.9	20.8

Figure 3: Annual average $PM_{2.5}$ (µg/m³) in 2022, compared with the previous years *(IQAir, 2022)*

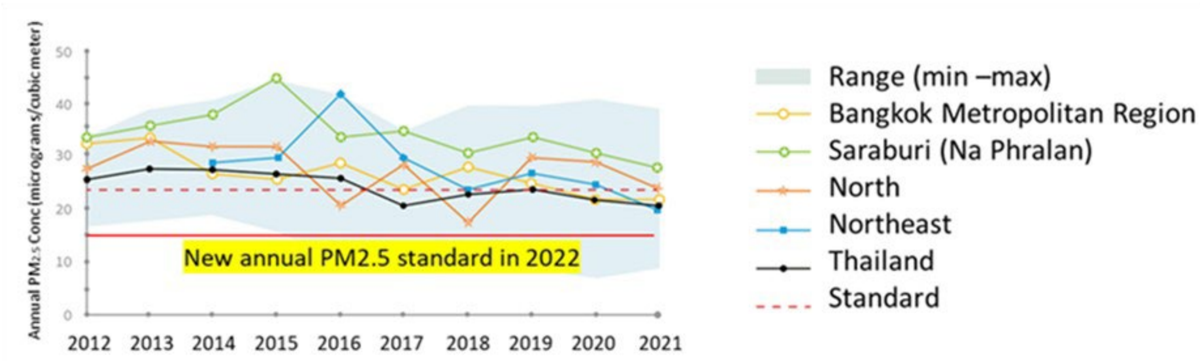

Figure 4: Annual $PM_{2.5}$ concentration in Bangkok and Thailand *(PCD, 2022)*

The improvement of air quality in Thailand during 2022 can be attributed to strict and effective policy interventions to mitigate air pollution. The relevant agencies successfully adopted these policies in accordance with the National Action Plan on $PM_{2.5}$ Reduction (2019) and the Contingency Plan for Particulate Matter Management (2021). For example, the policies and incentives promote non-burning in the agricultural sector, the promotional policies for electric vehicles, and the improvement of the rail system (PCD, 2022).

Current air quality in Bangkok

Bangkok is a megacity that has the highest population in Thailand, estimated at 9 million in 2020 (AQLI, 2022). Over the past five years (2018-2022), air quality in Bangkok has gradually improved (Figure 4). The concentration of $PM_{2.5}$ continually reduced from 27 µg/m^3 in 2018, followed by 26 µg/m^3 in 2019, 23 µg/m^3 in 2020, 23 µg/m^3 in 2021, and 22.7 µg/m^3 in 2022 (PCD, 2023). In addition, based on statistical data compiled from air quality measurements reported by IQ Air, Bangkok has experienced an improvement in air quality over the past 4 years. Figure 5 shows the percentage of hours that meet the WHO $PM_{2.5}$ guideline of 5 µg/m^3 increased from 5% in 2019 to 17.8% in 2022 due to different policies and the involvement of different sectors and stakeholders (IQAir, 2022).

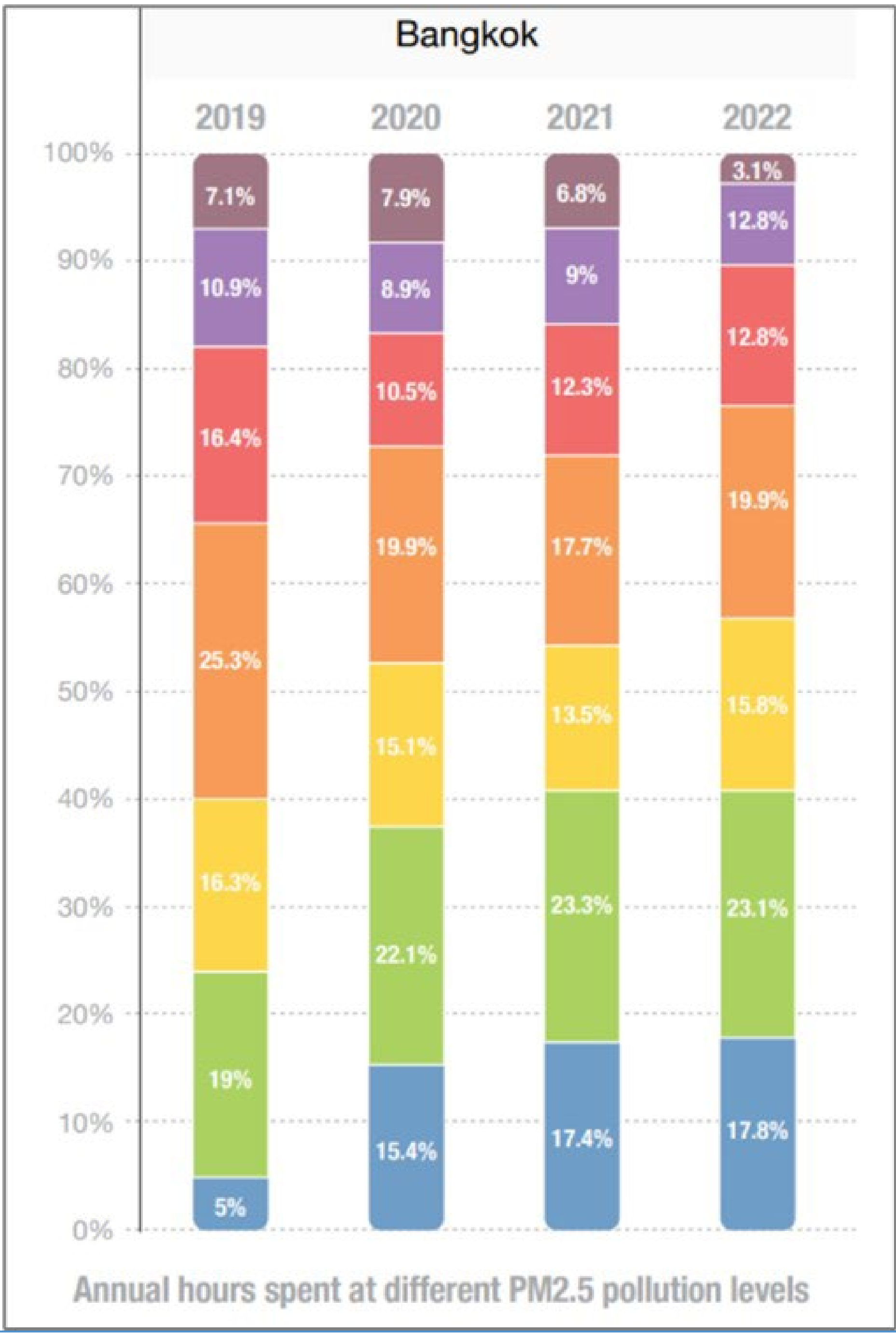

Figure 5: Annual hours spent at different $PM_{2.5}$ pollution levels *(IQAir, 2022)*

National Ambient Air Quality Standard (NAAQS)

Air Quality Management (AQM) in Thailand is prepared by different governmental agencies, with the Pollution Control Department as the main focal point. Thailand regulates NAAQS for six criteria air pollutants, as presented in Table 1 (PCD etc., 2018):

Table 1: Thailand Ambient Air Quality Standards (updated in June 2023)

Air Pollutants	1-hr	8-hr	24-hr	1-month	Annual
Carbon Monoxide (CO) (ppm)	30	9	-	-	-
Nitrogen Dioxide (NO_2) (ppm)	0.17	-	-	-	0.03
Sulfur Dioxide (SO_2) (ppm)	0.3	-	0.12	-	0.04
Total Suspended Particulates (TSP) (mg/m^3)	-	-	0.33	-	0.1
Particulate Matter < 10 microns (PM_{10}) (mg/m^3)	-	-	0.12	-	0.05
Particulate Matter < 2.5 microns ($PM_{2.5}$) (mg/m^3)	-	-	0.0375	-	0.015
Ozone (O_3) (ppm)	1.0	0.07	-	-	-
Lead (Pb) (mg/m^3)	-	-	-	1.5	-

On the 1st June 2023, the Pollution Control Department of Thailand, with the approval of the national pollution control board, revised the Thailand National Ambient Air Quality Standard for $PM_{2.5}$ from 50 $\mu g/m^3$ to 37.5 $\mu g/m^3$ for a 24-hour average concentration and from 25 $\mu g/m^3$ to 15 $\mu g/m^3$ for an annual average concentration, following Interim Target 3 set by the World Health Organization (IT3-WHO) (Table 2). The aim of improving the $PM_{2.5}$ standard is the enhancement and conservation of environmental quality in accordance with the National Environmental Quality Act of B.E. 2535 (1992).

Table 2: Ambient Air Quality of $PM_{2.5}$ Standards (Average $\mu g/m^3$).

	WHO Air quality guideline	Previous $PM_{2.5}$ std. in Thailand (IT2-WHO)	New $PM_{2.5}$ std. in Thailand (IT3-WHO)
24-hr	15	50	37.5
Annual	5	25	15

Major air pollution problems in Bangkok

Over the past ten years (2012-2021), air quality in Bangkok has gradually improved. The data from monitoring stations in Bangkok from PCD in 2021 showed that the concentration of six criteria air pollutants in Bangkok is well under the National Ambient Air Quality Standard, except for

Ozone and $PM_{2.5}$ (Figure 6). Ozone is another pollution concern in Bangkok. The overall trend of ozone in Thailand has been a steady decline over the past 5 years. However, in 2021, the level of ozone exceeded the standard and increased by 3% on average from the previous year, especially in the Bangkok area and Central region of Thailand (PCD, 2022). However, Ozone is a secondary air pollutant, forming in the atmosphere with the presence of precursor pollutants and sunlight. Thus, the control of Ozone is not as simple as primary air pollutants.

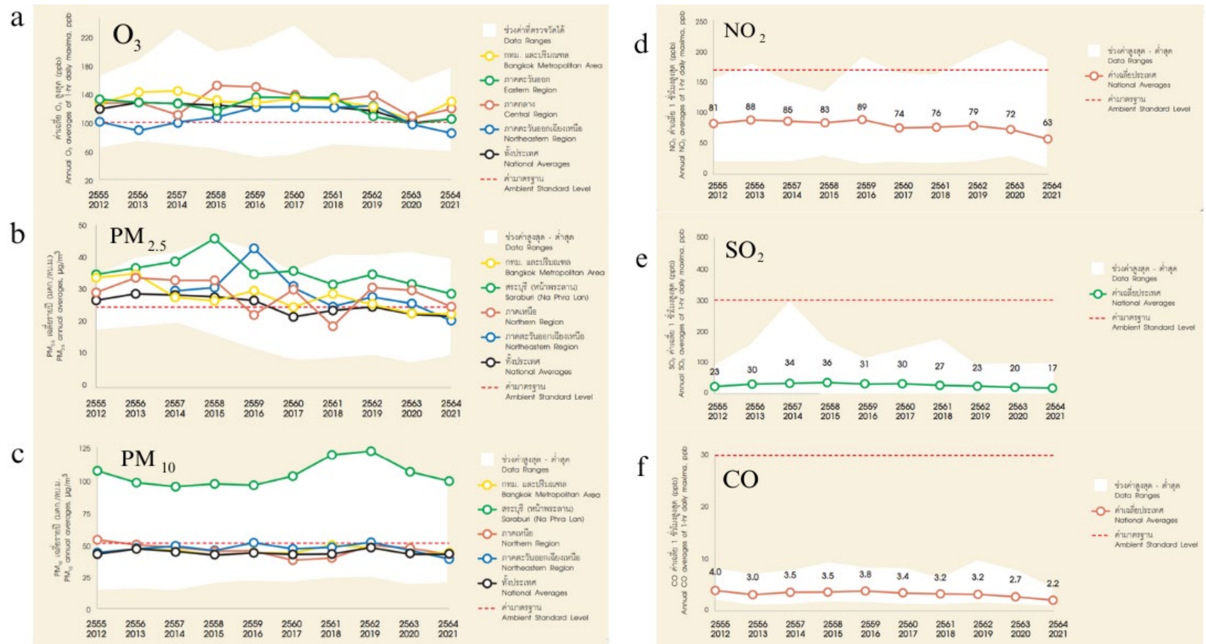

Figure 6: Annual average of six criteria pollutants in Thailand and Bangkok; a) Ozone, b) Particulate matter≤2.5µm, c) Particulate matter≤10µm, d) Nitrogen dioxide, e) Sulfur dioxide, and f) Carbon monoxide *(PCD, 2022)*

Major air pollution sources

The $PM_{2.5}$ problem in Bangkok can be attributed to two primary factors. First, meteorology contributes to the problem due to the air stagnation phenomenon and high air pressure spreading over Thailand during the dry season. This leads to a large accumulation of air pollution in the area. In February, $PM_{2.5}$ concentrations are high on several consecutive days in the central region of Bangkok and the vicinity of Thailand (PCD, 2018). Second, sources and human activities contribute to emissions in the area. The top three major pollution sources in Bangkok include transportation, industrial, and agricultural sectors (Nikam J. et al., 2021; PCD, 2018; Winijkut et al., 2020), as outlined below:

1. **Transportation Sector:**

   The transportation sector is one of the largest energy-consuming sectors in Thailand. Most on-road vehicles still rely on fossil fuel combustion, such as gasoline, diesel, and biodiesel. Although the number of electric vehicles is gradually increasing in Thailand, it is not significant enough to reduce pollution. Almost 50% of Thailand's population lives in urban areas, which have a high number of motorized vehicles, leading to associated air quality problems. It is estimated that road transport accounts for over half of $PM_{2.5}$ emissions (Nikam J. et al., 2021). Moreover, old in-use vehicles also contribute significantly to air pollution in Bangkok.

2. **Industrial Sources:**

   Industrial sources are key contributors to air pollutants due to their scale and the types of chemicals and processes used. The database from the Department of Industrial Works in December 2022 found 5,639 factories in the Bangkok area (PCD, 2022). Additionally, two hundred and sixty factories have the potential to emit high pollutants in the Bangkok area. It is estimated that the Industrial sector (Factories and Power plants) produces 12% of $PM_{2.5}$ emissions in Bangkok (Winijkut et al., 2020).

3. **Agricultural Sector:**

   The agricultural sector commonly disposes off agricultural residuals and wastes through burning, as the fastest approach, and one which also helps to control growth of weeds. However, this has severe consequences for air quality: incomplete combustion leads to the production of black carbon, $PM_{2.5}$, PM_{10}, ash, VOCs, and other pollutants. Since biomass burning occurs from November to April every year in Bangkok, which encourages a high risk of $PM_{2.5}$ during the dry season, known as the "burning season" (Nikam J. et al., 2021). Some locations in Bangkok are planting rice, i.e., Nong Chok District, Khlong Sam Wa district, and Lat Krabang district. It is estimated that the agricultural sector (Agricultural open burning) produces 20% of $PM_{2.5}$ emissions in Bangkok (Winijkut et al., 2020).

Figure 7 and Figure 8 show two emission inventories for Bangkok in 2018 (Figure 7) and 2019 (Figure 8). Although the contribution of each sector to total $PM_{2.5}$ emissions is not the same, the three major sources are similar.

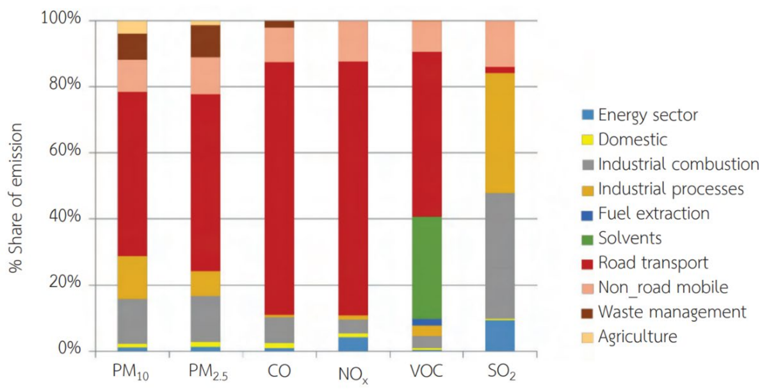

Figure 7: Air pollution sources in Bangkok and its vicinity in 2018 *(PCD, 2018)*

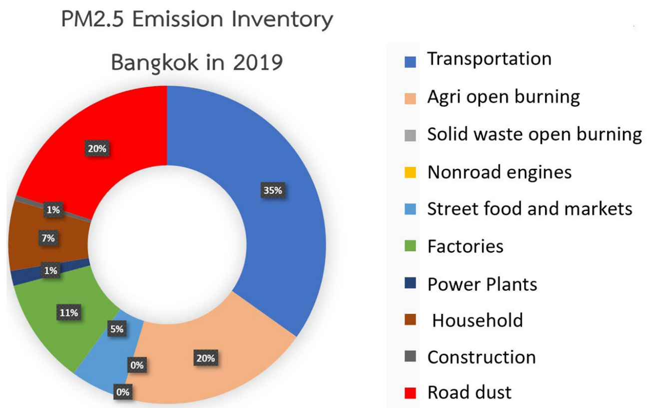

Figure 8: $PM_{2.5}$ Emission Inventory in Bangkok for the base year of 2019 *(Winijkut et al., 2020)*.

Bangkok Air Quality Plan

The 20-year Development Plan for Bangkok Metropolis (BMA , 2013) is a plan derived from people's vision regarding the development of Bangkok over the next 20 years as well as strategies for its implementation. Bangkok residents divided measures to drive the strategy into four five-year phases according to their priorities. This visionary plan is structured around six key dimensions:

1. Bangkok as a safe city
2. Bangkok as a green and convenient city
3. Bangkok as a city for all
4. Bangkok as a compact city
5. Bangkok as a democratic city
6. Bangkok as an economic and learning center

Strategy 1: Bangkok as a safe city. This strategy focuses on developing a better environment in Bangkok, free from pollution from wastewater, solid waste, and air pollution. The goal of the Bangkok Air Quality Plan in 2032 is that at least 80% of Bangkok residents living in inner-city areas will have fresh air equivalent to at least 200 days per year, especially for $PM_{2.5}$, to reduce its concentration by 15% in 2032 compared to the base year. Additionally, the effort in this plan is directed toward decreasing the levels of other air pollutants, as shown in Table 3.

Table 3: The goal of the 20-year Bangkok Air Quality Plan *(BMA , 2013)*

KPIs	5-year period 2013 – 2017	10-year period 2018 - 2022	15-year period 2023 - 2027	20-year period 2028 - 2032
1. Percent of 24-hour PM_{10} concentration lower than NAAQS at the ambient stations	Always	-	-	-
2. Percent of 24-hour PM_{10} concentration lower than NAAQS standard at the roadside stations	Not less than 95% of the monitoring data	Not less than 95% of the monitoring data	Not less than 98% of the monitoring data	Not less than 98% of the monitoring data
3. Percent exceedance of 24-hour $PM_{2.5}$ concentration	Base year	5% reduction from the base year	10% reduction from the base year	15% reduction from the base year
4. Percent of 8-hour ozone (O_3) concentration lower than the NAAQS	-	100%	100%	100%
5. Percentage exceedance of 1-hour nitrogen oxide (NO_2) concentration at roadside station lower than NAAQS	Base year	5% reduction from the base year	10% reduction from the base year	15% reduction from the base year
6. Annual benzene concentration lower than NAAQS	Base year	5% reduction from the base year	10% reduction from the base year	15% reduction from the base year

The next section of the report discusses the technologies that can be used to reduce emissions at the sources in Bangkok. Emphasis is provided for the three major emission sources in Bangkok: transportation, open burning, and industry. However, considering the importance of cooking and street food in Bangkok, cleaner cooking technologies are also discussed in the next section.

2. LIST OF THE TECHNOLOGIES THAT CAN BE USED TO REDUCE EMISSIONS IN BANGKOK

1. Low-cost Sensor for ambient air quality monitoring: Thai sensors & EANET

From the National Agenda for action plans "Solving the dust pollution problem" in Thailand for the period 2019-2024, Thailand has implemented measures to enhance the efficiency of air quality management. This measure considered the suitability of using Low-Cost Sensors (LCS) for air quality monitoring (PCD, 2019). Additionally, the Ad Hoc Plan for Solving the Dust Pollution Problem in Bangkok in 2023 also addressed the $PM_{2.5}$ problem in Bangkok by expanding the monitoring and alert system to 1,000 locations (currently, there were 557 locations) (BMA, 2022). Furthermore, Thai law requires $PM_{2.5}$ and PM_{10} monitoring devices certified by USEPA to report the 24-hour concentration to the public. However, due to the high costs of the monitoring device, operation, and maintenance, the Pollution Control Department, which is the main agency responsible for air quality management in Thailand, cannot expand the monitoring stations to cover all areas. The LCS air quality monitoring system can help expand the monitoring network and provide an air quality alert system at a provincial level.

Currently, different organizations in Thailand, such as Sensor for All developed from Chula University (CUSense, 2023), Dust boy developed from Chiang Mai University (CCDC, 2023), and EANET, have conducted different research to further develop the LCS for better uses (Figure 9). Most models of LCS are based on the light scattering approach. When the light passes through particles, it scatters (Figure 10). The scattered light is concentrated on a highly sensitive photodiode, which is then amplified and analyzed by a circuit. The $PM_{2.5}$ mass concentration was calculated from the distribution of light scattering intensity by considering the relationship between scattering intensity and particle size (Trilles S. et al., 2019; Nakayama T. et al., 2017). In addition, the United States Environmental Protection Agency (U.S. EPA) was comparing the performance and cost between monitoring stations and low-cost sensors in Table 4 (Clements et al., 2022).

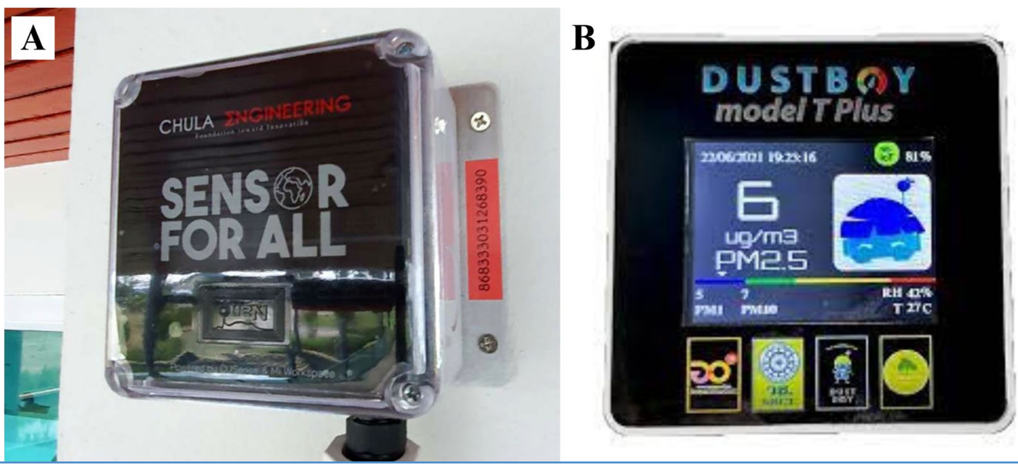

Figure 9: Low-Cost Sensor for $PM_{2.5}$ monitoring in Thailand: A) Sensor for All developed by Chulalongkorn University; B) Dust boy developed by Chiang Mai University

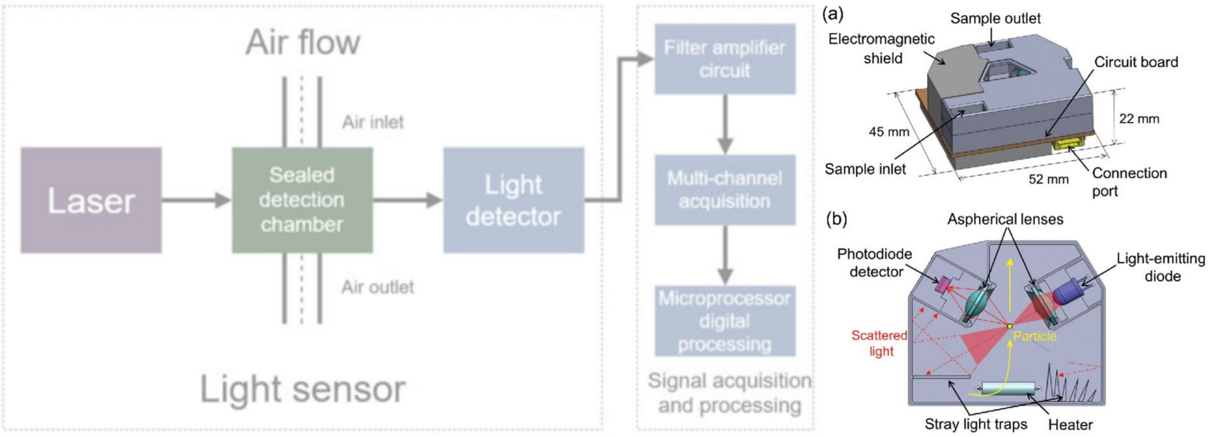

Figure 10: Concept of the low-cost sensor

Table 4: Comparison Between Monitoring stations and Low-Cost Sensors *(Clements et al., 2022)*

Consideration	Monitoring stations	Low-Cost Sensors
Typical Purchase Cost	$15,000 to $40,000 (U.S. Dollars)	$100 to $5,000 (U.S. Dollars)
Staff Training for Operation	Highly trained technical staff	Little or no training (user guide/manual may help)
Operating Expense	Expensive – need for shelter, technical staff, maintenance, repair, quality assurance	Less expensive – need for device replacement or repair, data streaming, data management
Siting Location	Fixed location (building/trailer needed)	More portable (with basic weather protection)
Data Quality	Known and consistent quality in a variety of conditions	Unknown and may vary from sensor to sensor in different weather conditions and pollution environments
Operating Lifetime	10 years or more (Calibrated and operated to maintain accuracy)	Short (pollutant dependent; <1-3 years) (may become less accurate over time)
Used for Regulatory Monitoring	Yes	No

Advantages of low-cost sensors are as follows:

- Sensors are relatively low-cost, affordable, easy to operate, and portable. They have low maintenance costs and have a lifespan of around 3-5 years. They are widely used at present (Yawootti A. et al., 2019; thaipost, 2020). The price of the LCS ranges from 5 to 100 USD (Trilles S. et al., 2019), compared with the standard monitoring stations with a capital cost of 146,200 USD per station and operational costs ranging from 4,200 to 27,200 USD per station (ADB, 2013).
- Sensors are easy to install both indoors and outdoors. They have low power consumption and produce minimal noise during operation. They provide real-time measurement data and have remote data transmission capabilities, allowing notification in real time to the public in the area affected by particulate matter pollution (Yawootti A. et al., 2019).
- Sensors can be used to raise public awareness of air pollution by providing alerts and concerns about health impacts.

Disadvantages of low-cost sensors are as follows (EANET, 2023a; EANET, 2023b; EANET, 2022; Yawootti A. et al., 2019)**:**

- LCS has low accuracy and inaccuracies in reading values when compared with the monitoring station, especially during periods of increased particulate matter concentration. This can lead to confusion and misunderstanding among the public due to inconsistent measurement values.
- LCS has different qualities and performances.
- There is no calibration, no QA/QC, and no standardization, and tends to give much higher readings than the standard monitor at high concentrations.
- LCS is affected by humidity.
- Air volume and density of particles required for converting particle numbers to particle mass are required.
- The reading depends greatly on where it is placed; placing it closer to the source will have a higher concentration.
- Instantaneous and short-term (less than 24 hours) readings may not have any meaning with regard to health effects.
- There are issues related to data interpretation and presentation.

2. Diesel Particulate Filter (DPF) for diesel vehicle emission control

The Diesel Particulate Filter (DPF, Figure 11) is a device that reduces diesel particulate matter or soot from the exhaust gas of a diesel engine. They can be fitted to both new and in-used vehicles (retrofitted) (EU, 2022; Majewski, 2020). The DPF filters the exhaust emission, and the particulate matter is trapped within the filter. There are two main types of filters (Figure 12):

A 'full' DPF, which can reduce PM emissions between 85% and 99%. It is also very effective at reducing emissions of small particles, which are of the greatest health concern. It is available for new vehicles from the factory or for retrofitting in-use vehicles.

A 'partial' filter can reduce PM emissions between 30% and 50%. It may not be able to reduce small particles as efficiently as the larger particles but is available for use in in-use vehicles with a moderate emission level.

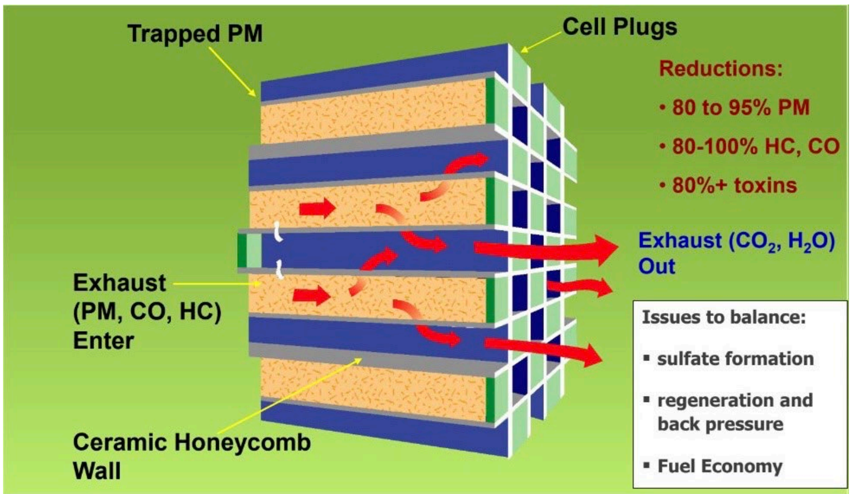

Figure 11: Diesel Particulate Filter for diesel vehicle emission control (DPF)

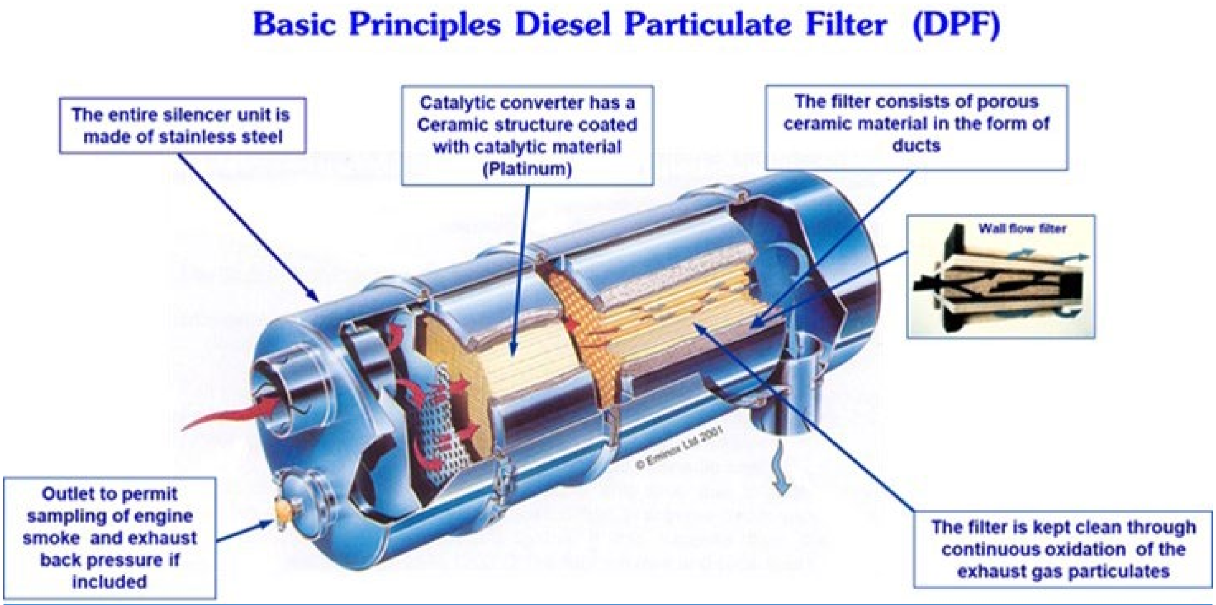

Figure 12: Schematic representation of a diesel particulate filter

From the National Agenda for action plans "Solving the dust pollution problem" in Thailand for the period 2019-2024, Thailand has promoted research and development of technological advancements in monitoring, analysis, and innovation to reduce air pollution. It aims to apply these advancements to improve air quality management, including dissemination and public communication of knowledge. There were pilot projects to test the feasibility of installing Diesel Particulate Filters (DPF) in in-used vehicles in Bangkok (PCD, 2019). The demonstration project installed DPFs on 4 in-use trucks (Euro II and III) and 2 buses (Euro II). The results show that black smoke, PM, particle number, CO, HC, and NOx were reduced by 100%, 83%, 97%, 98%, 60%, and 7%, respectively (PCD, 2022).

Chavanaves (2021) estimated $PM_{2.5}$ emission reduction in Bangkok based on the assumption that all in-used diesel vehicles older than Euro IV would install DPFs. The results are shown in Figure 13 as Scenario 8 (All Diesel vehicles older than Euro IV are fitted with DPF) and Scenario 8+1 (All Diesel vehicles older than Euro IV are fitted with DPF and sulfur in the fuel is reduced to 10 ppm).

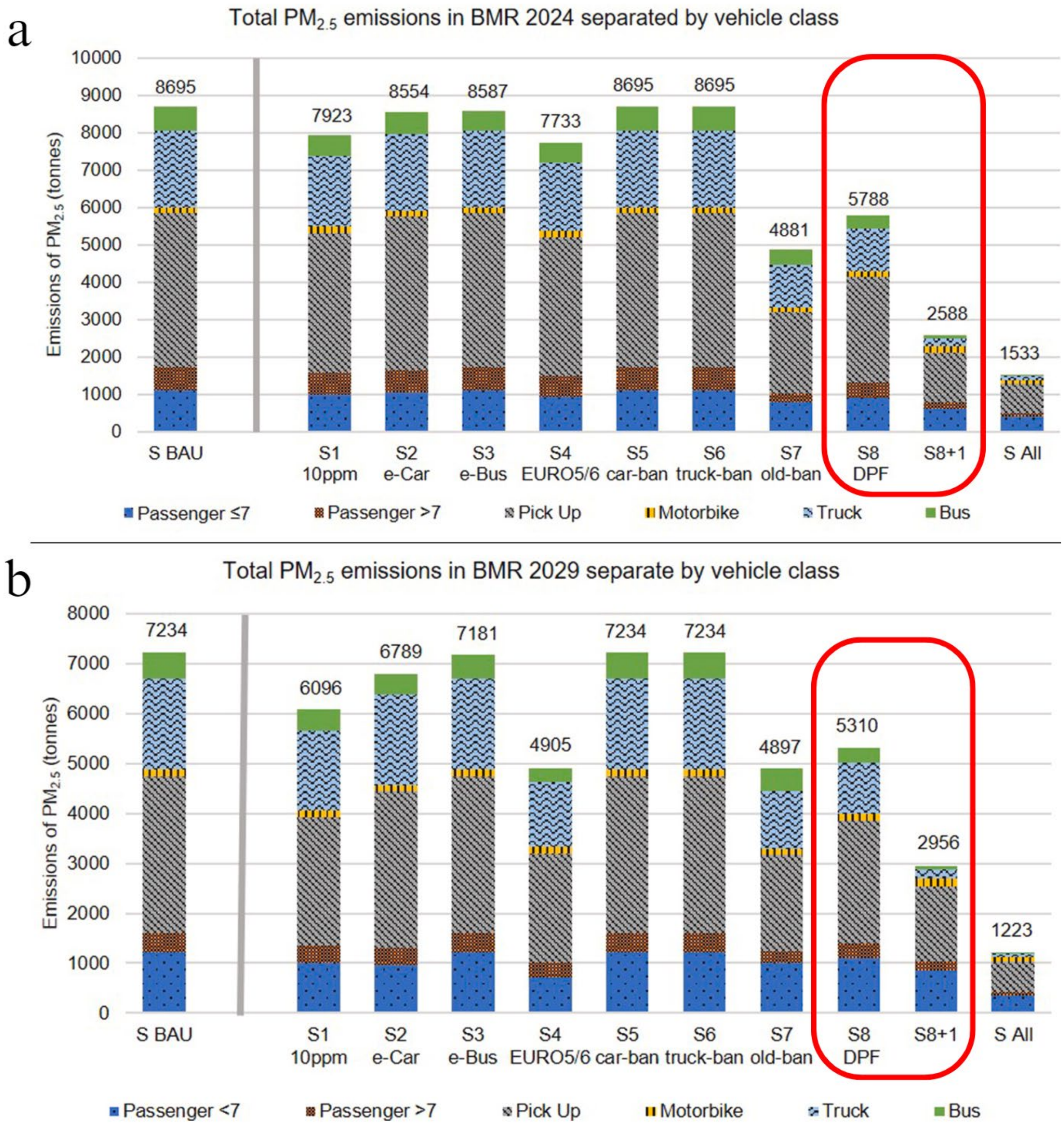

Figure 13: Prediction of $PM_{2.5}$ emission reduction with different scenarios: **a)** 2024 and **b)** 2029 *(Chavanaves et al., 2021)*

In their analysis where DPFs were retrofitted onto ≤ Euro III diesel engines, emissions could be reduced by over 33%, and when applied together with ultra-low sulfur fuel (10 ppm), emissions could be further reduced to over 70%. Additionally, this scenario is the second-best scenario, reducing $PM_{2.5}$ emissions by over 4,200 tons in 2029, showing that if DPF performs at full efficiency, it could substantially reduce $PM_{2.5}$ emissions (Chavanaves et al., 2021).

However, the technological possibility of using DPF with in-used vehicles older than Euro II has not been discussed in their study. In-used vehicles older than Euro II emit very high PM, which will clog the DPF very fast and may need very frequent regeneration, making it uneconomical to use.

Advantages of DPF are as follows:

- Proven Technology: DPF is a technology used worldwide (Suwanthada P. et al., 2022). In 2018, 40% of new heavy-duty diesel vehicles (HDDVs) sold worldwide were equipped with DPFs, and from the prediction, it would increase to 50% in 2021 as shown in Figure 14.

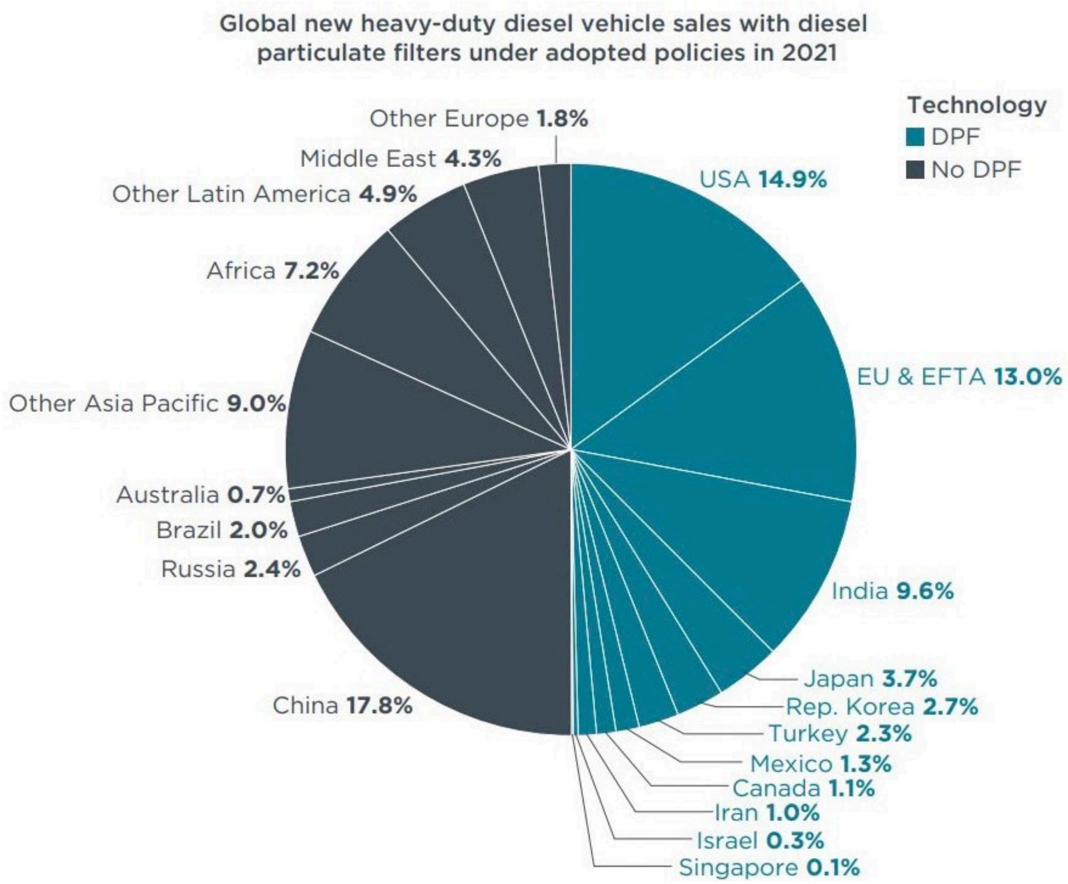

Figure 14: Global new heavy-duty diesel vehicle sales with diesel particulate filters under adopted policies in 2021 *(Joshua Miller&Lingzhi Jin, 2018)*

- Exceptional Reduction of PM: California Air Resources Board (CARB)-Verified DPFs exhibit an impressively high efficacy in reducing PM emissions in diesel exhaust, achieving up to a remarkable 99% reduction.
- Versatile Range of Applications: DPFs demonstrate their effectiveness across a diverse array of vehicles globally, spanning from buses and heavy-duty trucks to off-road vehicles.
- Cost-Efficient Solution: DPFs offer a cost-effective alternative to vehicle replacement. Furthermore, they substantially contribute to community health by significantly diminishing the negative impacts of PM on affected individuals.
- Straightforward Installation: Certain DPF models can be easily installed by qualified dealers, streamlining the process of achieving emissions reduction and compliance with local emission regulations.
- Robust Longevity: The majority of DPFs are engineered to endure up to 150,000 miles before necessitating cleaning. In specific cases, cleaning may not even be required under normal usage conditions. These systems are designed to match the vehicle’s lifespan on which they are installed.

Disadvantages of DPF are as follows:

- Low Super Absorbent Polymer (SAP) lubricants are required (Signer M., 2016) (Signer M., 2016).
- Fuel quality sensitive (passive regeneration) (Signer M., 2016). The amount of PM is the cause of DPF clogging and reduces the efficiency of trapping soot. Therefore, clean fuels are very important—this technology requires clean fuel containing sulfur less than 15 ppm (DPF Clean, 2023).

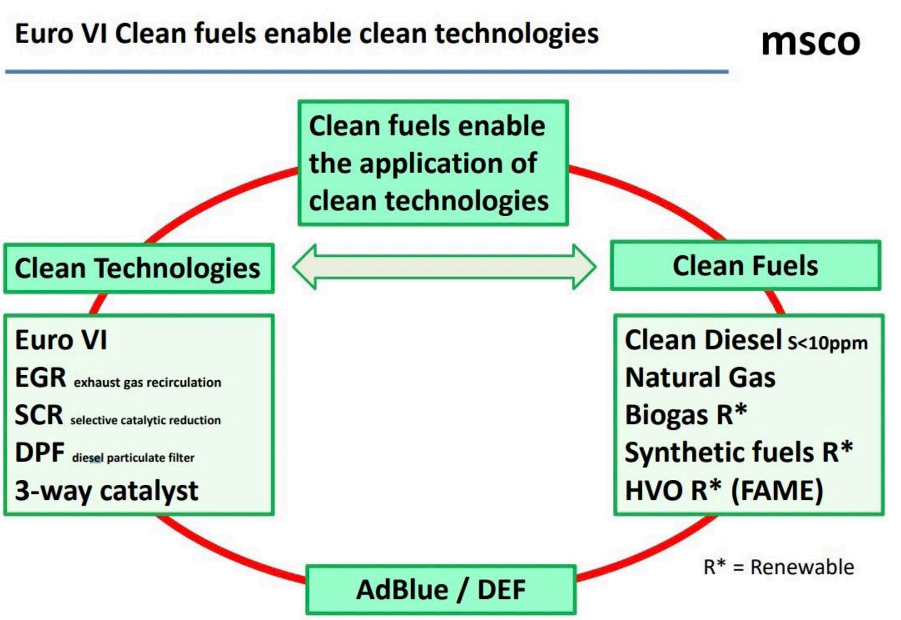

Figure 15: Clean technologies to increase the efficiency of the device *(Signer M., 2018)*.

- Maintenance requirements after 300,000 – 500,000 km (Signer M., 2016). The DPF can become clogged over time and require replacement or cleaning. The cost of a DPF can vary depending on the make and model of your vehicle. On average, the cost of DPF filter replacement can range from $2,000 to $4,000, while the cost of DPF cleaning is around $179 to $500 for most models (DPF Clean, 2023).
- DPF is not suited to install with a car that only does short journeys or is in stop/start traffic quite frequently. Eventually, the engine can lose power and stop (Carbase, 2023).
- Many studies have shown that controlling emissions through exhaust systems often yields limited results. Therefore, engine improvements have proven to be more effective, such as optimizing fuel injection pumps, injector designs, and combustion chamber configurations (Suwanthada P. et al., 2022).

3. Low Emission Zones

Low Emission Zones (LEZs) are areas where only vehicles meeting the minimum emission standards are allowed to enter freely. Polluting vehicles that fall below the standards must pay an entry fee or are banned from entering the zone. Usually, LEZs are implemented in phases, with progressively stricter regulations. To enforce them, an Automatic Number-Plate Recognition system or a color-coded sticker visible on the vehicle's windshield is typically used to identify the vehicle classification. LEZs are used most prominently in Western Europe (Figure 16) by a large margin, with hundreds currently in operation (EU, 2022; Phanich, 2022). Most of these LEZs set Euro IV as the minimum entry requirement for diesel vehicles. Though not very common in Asia, Beijing established an LEZ targeting Euro I and Pre-

Euro vehicles in preparation for the 2008 Olympics and recently upgraded to a stricter China III (close to a Euro III equivalent) minimum requirement (Phanich, 2022). For the costs of implementing and operating LEZs, the costs of setting up and running the low-emission zone in London are estimated at £2.8 million to set up (3,440,878 USD) with running costs of £4 million (4,913,700 USD) each year. The main budget was used to set up a network of cameras across the LEZ of London to recognize vehicles through cameras (Watkiss et al. , 2003).

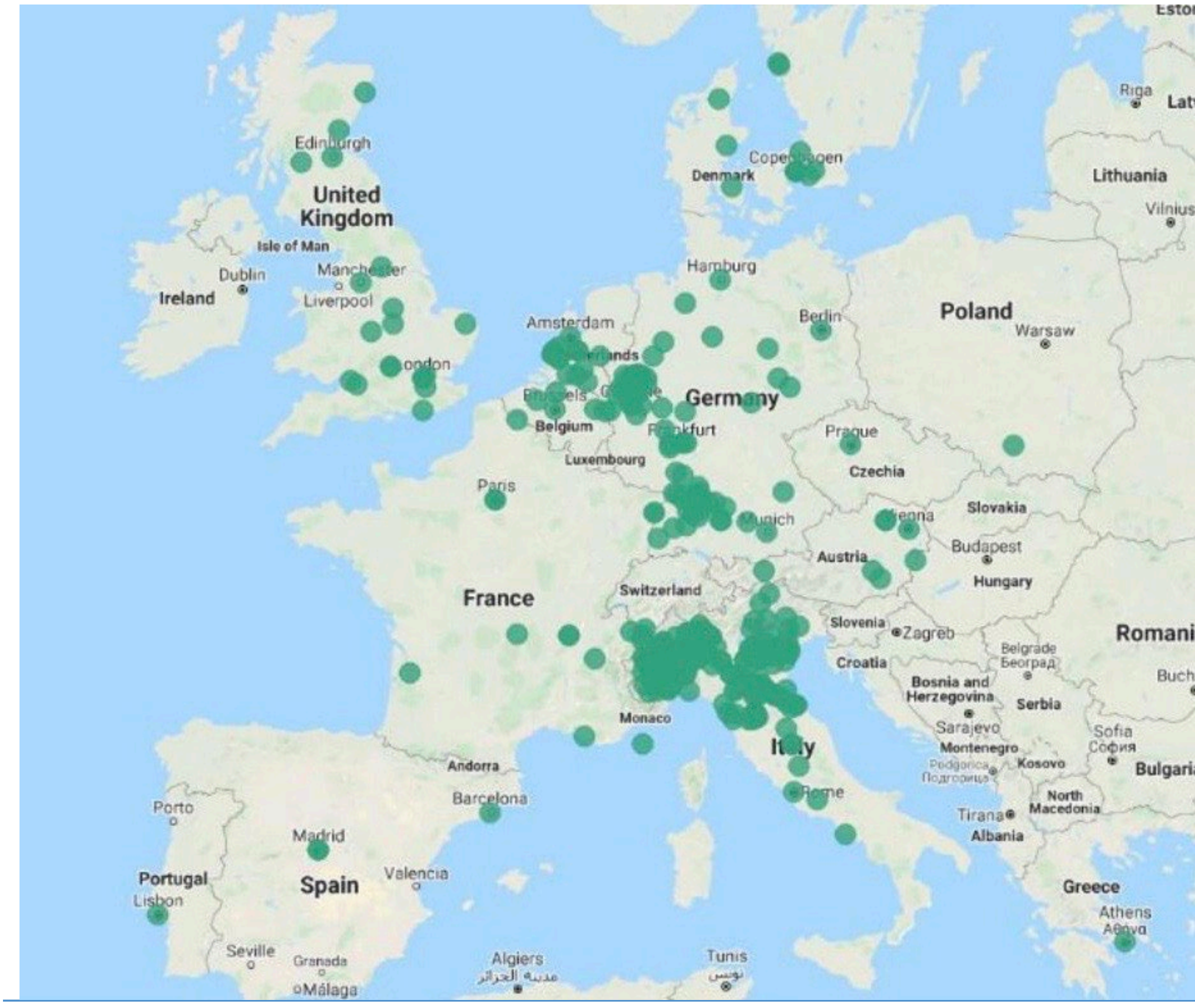

Figure 16: Map of Low Emission Zones in Europe *(EU, 2022)*.

From the National Agenda for action plans "Solving the dust pollution problem" in Thailand for the period 2019-2024, Thailand has implemented measures to enhance the efficiency of crisis-oriented area management (PCD, 2019). This measure includes reducing the number of private cars during rush hours in the Low Emission Zone, which would be implemented when $PM_{2.5}$ dust concentration reaches level 3 (51-75 $\mu g/m^3$) or higher. Based on the Ad Hoc Plan for Solving the Dust Pollution Problem in Bangkok 2023 (BMA, 2022), the implementation includes:

1. Encouraging cooperation from the private sector to promote "Work from Home" arrangements and aiming for more than 60% of government employees to work from home.
2. Promoting discounted prices and encouraging the use of public transport.
3. Providing shuttle bus services in certain areas.

On January 20, 2022, the Bangkok Metropolitan Administration (BMA) signed a memorandum of understanding (MOU) with 21 public-private agencies, including the Pollution Control Department (PCD), to announce a pilot project for the Low Emission Zone (LEZ). The project is limited to the Pathumwan district, covering an area of 8.4 square kilometers. Although the project's primary goal is to raise public awareness of LEZs and is relatively small in scale, these activities demonstrate that the Thai government is considering the possibility of implementing a full-scale LEZ policy (ThaiHealth Official, 2022).

The possibility of reducing $PM_{2.5}$ by banning Pre-Euro and Euro I vehicles from entering the Bangkok area has been explored in a study by Sukitpannenit and Stettler (2020). The research indicates that diesel vehicles in the Pre-Euro and Euro I categories are significant sources of $PM_{2.5}$, as shown in Figure 17 and Figure 18. Therefore, restricting the entry of such vehicles into the area could potentially reduce $PM_{2.5}$ levels by up to 55% for diesel passenger cars, 60% for diesel light-duty trucks, 50% for diesel heavy-duty trucks, and 65% for diesel buses. However, this research estimates emission reduction based on the number of vehicle technologies, which may not be similar to the real environmental conditions.

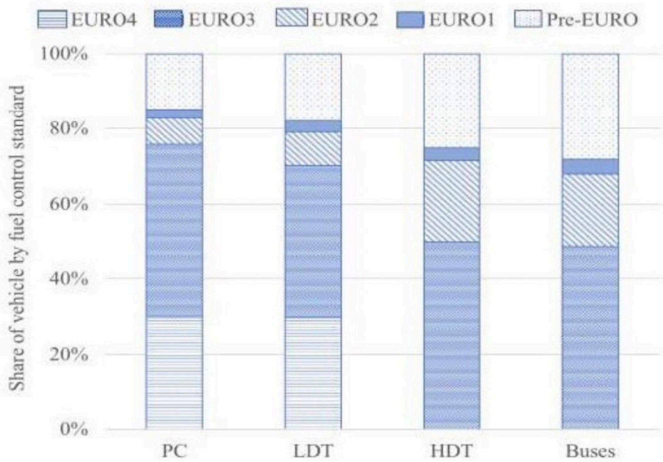

Figure 17: The 2017 Bangkok Metropolitan Region (BMR) vehicle fleet, consisted of passenger cars (PC), light-duty trucks (LDT), heavy-duty trucks (HDT), and buses, classified by standards.

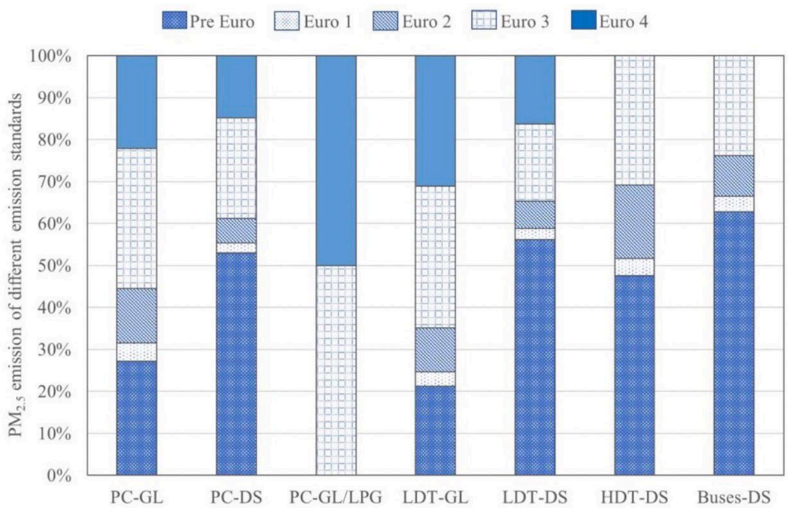

Figure 18: $PM_{2.5}$ emissions by vehicle-fuel types and emission control standards. Remark: GL= gasoline; DS=diesel; LPG = liquefied petroleum gas

However, there is another research showing that the amount of $PM_{2.5}$ emission would not reduce if the Low Emission Zone (LEZ) is adopted in Bangkok (Chavanaves et al., 2021), but moving high pollutant-emitting vehicles, such as diesel cars and trucks, out of Bangkok. Thus, the total health damage to the population could be reduced even when net emissions to the Bangkok Metropolitan Region (BMR) remain constant. From Figure 19, Scenarios 5 (all diesel private vehicles, except Euro V and Euro VI, are banned from Bangkok city, assuming removed vehicles are added to the roads of 5 surrounding provinces with equal distribution) and Scenarios 6 (all diesel trucks, except Euro 5 and Euro 6, are banned from Bangkok city, assuming removed trucks are added to the roads of 5 surrounding provinces with equal distribution) are zoning policies, where vehicles are banned from Bangkok and transferred to the surrounding provinces. Hence, the scenarios change the location of emission sources, while the total number of vehicles and total emissions in the whole BMR region remain constant. On the other hand, banning old cars more than 20 years old will effectively reduce $PM_{2.5}$ emissions if adopted and implemented in the long term (Scenario 7, old cars ban).

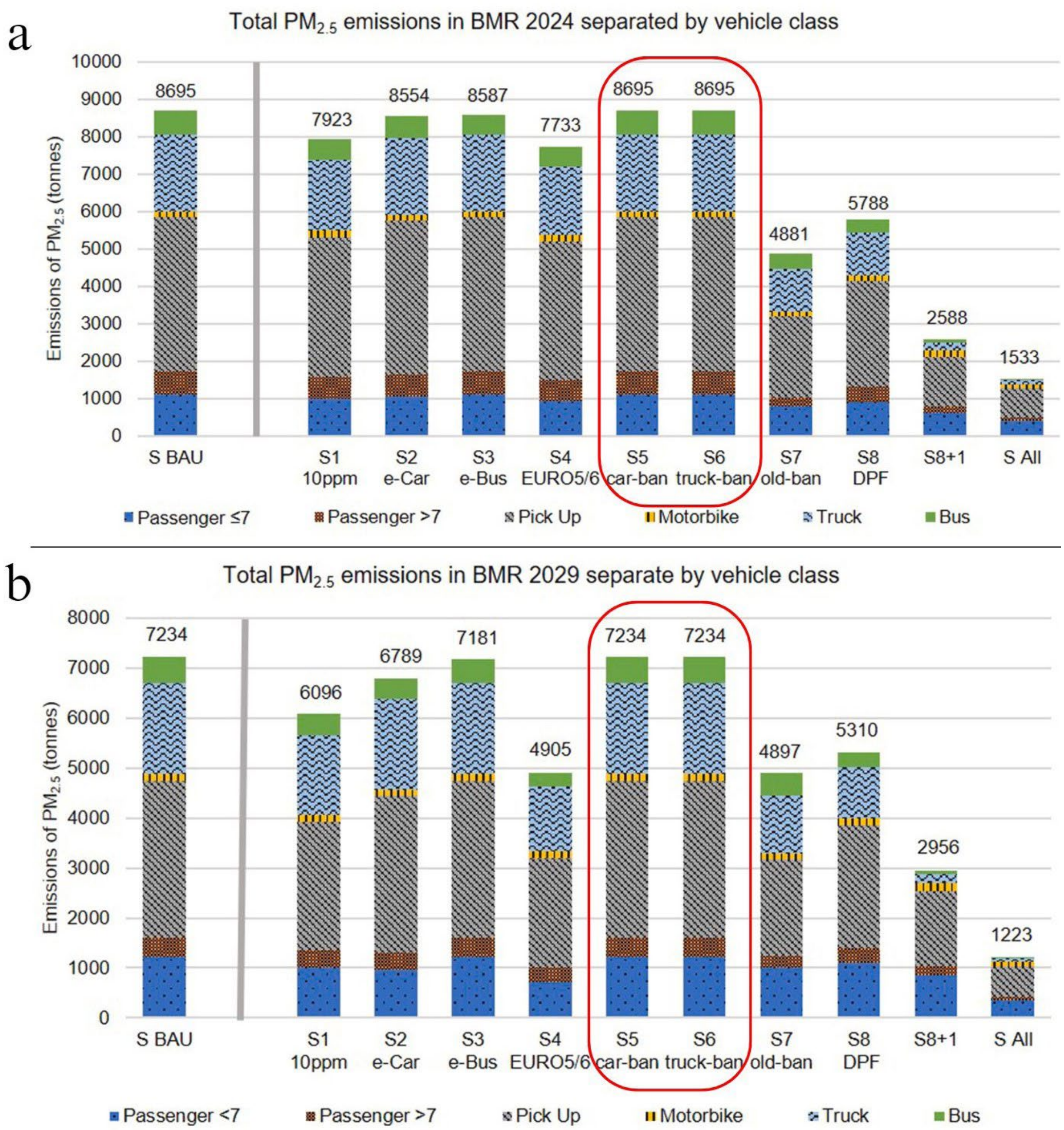

Figure 19: Prediction of $PM_{2.5}$ emission if adopt LEZ implement in the Bangkok area: **a)** 2024 and **b)** 2029 *(Chavanaves et al., 2021)*

Advantages of Low-Emission Zone are as follows:

- Control directly at the source of $PM_{2.5}$. Low-emission zones reduce emissions of fine particles, nitrogen dioxide, and (indirectly) ozone (EU, 2022).
- Encourage people to repair or choose a car meeting emission standards (for example, whether they choose to buy a new vehicle, retrofit in-used vehicles, or buy a second-hand vehicle that meets the standard, change fuel type) (EU, 2022).
- Reduced air pollution has been linked to a number of health concerns, such as respiratory problems and heart disease (Elite garages, 2023).
- Reduced noise pollution, which is known to cause several problems, including sleep disturbance, stress, anxiety, and cardiovascular disease (Elite garages, 2023).
- Ultra-low emission zones can improve the quality of life by making cities cleaner, quieter, and more pleasant places to live (Elite garages, 2023).

Disadvantages of a Low-Emission Zone are as follows:

- Limitation of public transport in Low emission zones will affect the convenience of citizens (EU, 2022).
- Low emission zones are enforced either with camera systems or manually, usually together with windscreen stickers. In some zones, it is necessary to register or buy a sticker before entering. In most zones, foreign vehicles are affected as along with national vehicles (Dieselnet, 2023).
- The cost of upgrading or replacing vehicles that don't meet the necessary emission standards (Elite garages, 2023).
- Rerouting journeys to avoid ULEZs is inconvenient and can often extend trips considerably (Elite garages, 2023).
- The financial impact on businesses that rely on delivery vehicles that don't meet the standards (Elite garages, 2023).

4. Electric Vehicles

Transportation is a major source of carbon emissions. Electric vehicles are one solution to reducing the air pollution and greenhouse gas emissions caused by Internal Combustion Engine Vehicles (ICEV) (Suwanthada P. et al., 2022). There are three main types of electric vehicles: Plug-In Electric Vehicles (PHEVs), Hybrid Electric Vehicles (HEVs), and All Electric Vehicles (BEVs), as shown in Figure 20. For Plug-In Electric Vehicles (PHEVs) and Hybrid Electric Vehicles (HEVs), they still use fossil fuel for energy but emit less exhaust gas from combustion. All-electric vehicles, or 100% electric vehicles, do not need fossil fuel for energy and can be separated into two types. First, Battery Electric Vehicles (BEVs) (Figure 21) use a large traction battery pack to power the electric motor and must be plugged into a wall outlet or charging equipment, also called electric vehicle supply equipment (EVSE). Because they run on electricity, these vehicles emit no exhaust from a tailpipe and do not contain typical liquid fuel components, such as a fuel pump, fuel line, or fuel tank. Second, Fuel Cell Electric Vehicles (FCEVs) combine hydrogen and oxygen to produce electricity, which powers the motor. Emissions are simply water vapor and warm air (Parajuly et al., 2020; Suwanthada P. et al., 2022; EERE, 2023).

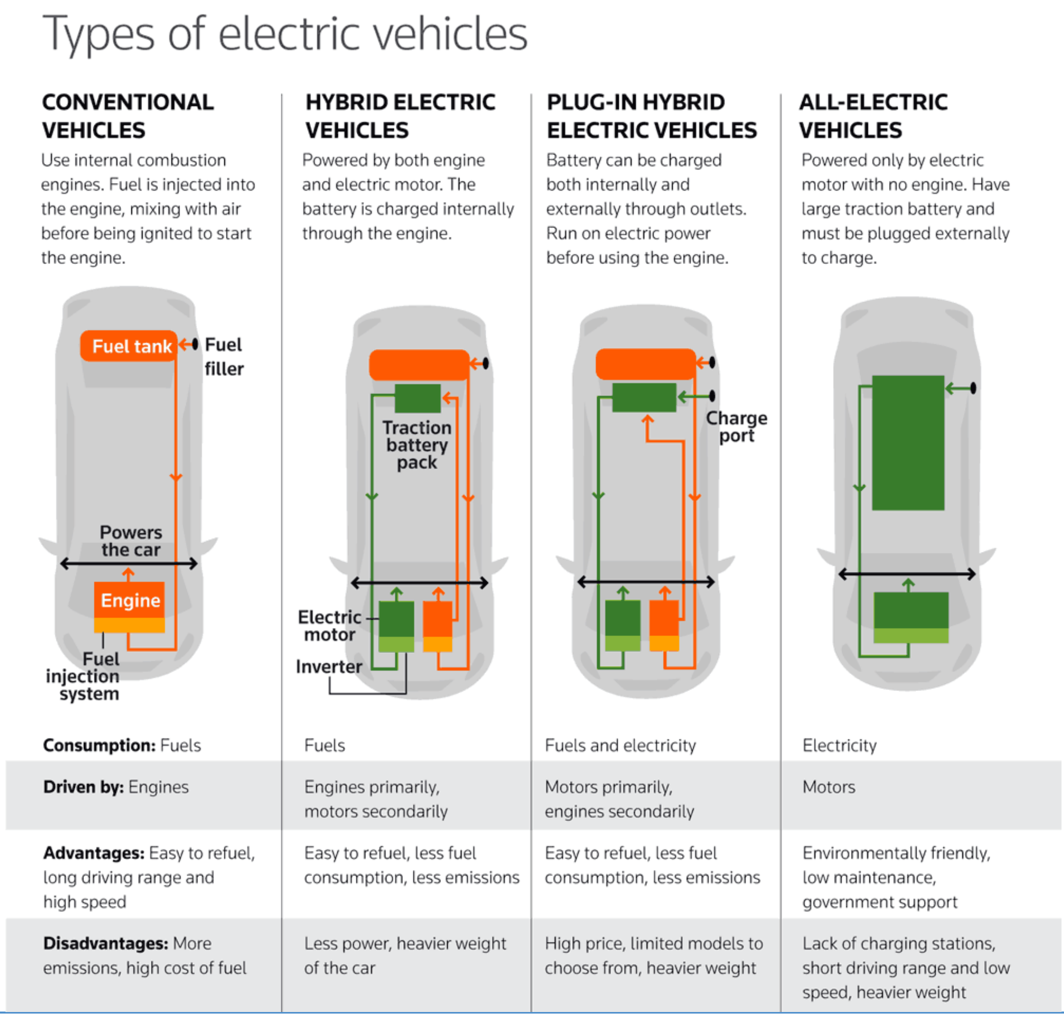

Figure 20: Type of electric vehicles (*Source*: Reuters Graphics and U.S. Department of Energy)

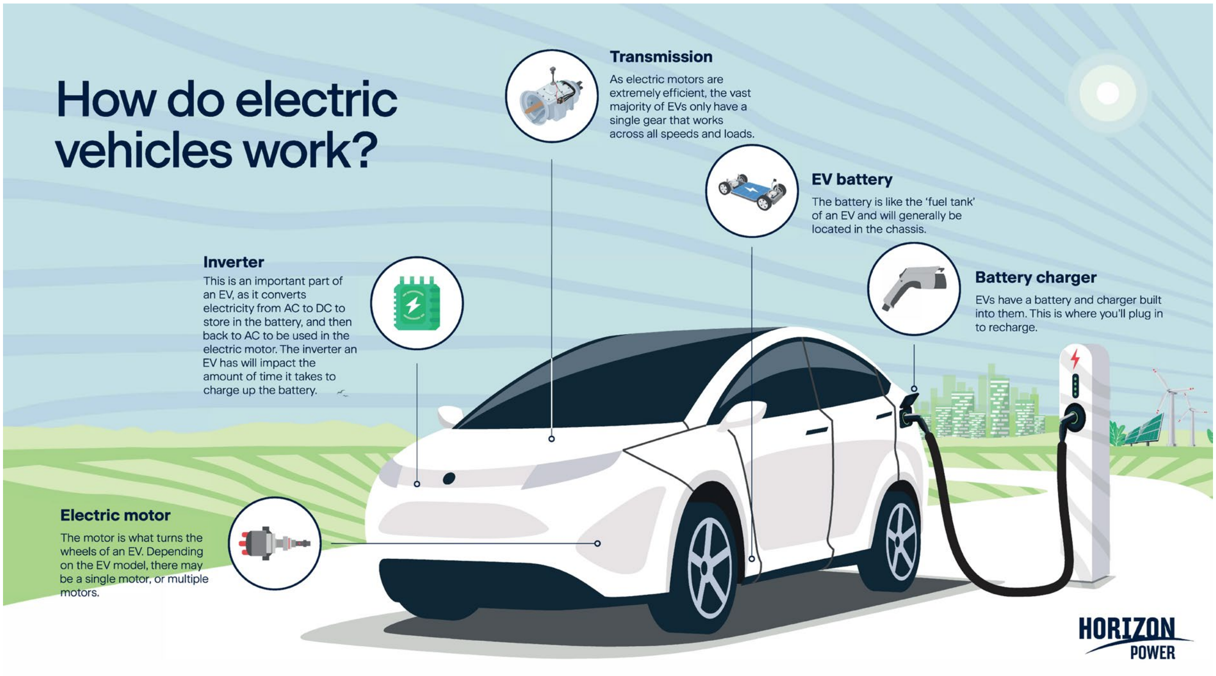

Figure 21: Battery electric vehicles (BEVs) *(Horizon power, 2023)*

From the National Agenda for action plans "Solving the dust pollution problem" in Thailand for the period 2019-2024, measures have been implemented with a focus on preventing and reducing pollution at the source. One strategy for controlling and reducing pollution from vehicles involves the procurement of electric vehicles to replace aging government vehicles (PCD, 2019). Additionally, efforts are being made to promote the use of electric vehicles in the Bangkok area through the EV-Ecosystem initiative (BMA, 2022).

In February 2020, Prime Minister Prayut Chan-o-cha appointed the Electric Vehicle Association of Thailand (EVAT) to set a direction and target for the EV shift towards Zero-Emission Vehicle (ZEV). Under the government's 30:30 electrification policy, all vehicles used by government agencies and public fleets, as well as 30 percent of all new vehicles produced in Thailand, must be ZEVs by 2030 (Suwanthada P. et al., 2022; The Nation, 2023a). The implementation plan includes the following stages:

- The first stage aims to promote the use of electric motorcycles and establish nationwide infrastructure support.
- The second stage (2013-2025) focuses on developing the electric vehicle industry with the goal of producing 225,000 electric cars, 360,000 electric motorcycles, and 18,000 electric buses/trucks by 2025. This also includes battery production to support domestic manufacturing and achieve economy of scale.
- The third stage (2026-2030) aims to drive the plan and measures towards achieving the 30/30 policy. The goal is to produce a total of 725,000 electric cars and trucks and 675,000 electric motorcycles by 2030, accounting for 30% of the production volume. Battery production will also be part of the domestic manufacturing plan.

Regarding the action plan for electric vehicles in public transportation, the transport minister aims to increase the number of electric buses across Greater Bangkok to 8,000 within three years (from 2022). The electric buses will replace the fleet of diesel vehicles that have been in service for more than 20 years, as more than 2,000 Bangkok buses are over 20 years old, contributing to $PM_{2.5}$ emissions (The Nation, 2022). As of the current situation in 2023, Thai Smile company operates 1,250 electric buses on 71 routes, and they plan to expand their fleet to 3,100, covering a total of 122 routes this year (The Nation, 2023b).

Regarding the cost of electric vehicles available in Thailand, the price range for EV cars from 38 brands is estimated at 325,000 to 8,099,000 Baht (9,148 to 227,958 USD) (EVAT, 2023). King Mongkut's Institute of Technology Ladkrabang and Bangkok Mass Transit Authority studied the guidelines for providing 200 electric buses in Thailand, and their estimated price for electric buses is 10.76 million Baht per unit (302,332 USD/unit). Additionally, the maintenance cost for electric buses in the first 5 years is estimated to be around 652.50 Baht per unit per day (18.33 USD/unit/day), and in the subsequent 6-10 years, it is estimated to be approximately 1,272.30 Baht per unit per day (35.75 USD/unit/day) (KMITL, 2016).

Figure 22: Electric Buses in Bangkok

Another alternative public transportation in Bangkok is the electric ferry. The Bangkok Metropolitan Administration (BMA) has introduced an electric ferry service for passengers to avoid rush-hour traffic. There are two routes for the electric boat service, one along the river and another along a canal. The first route covers ferry service on the Chao Phraya River, spanning a distance of more than 20 km, connecting Sathorn to Phra Nang Klao (Nonthaburi district). This route has 12 stops with 4 platforms linking either the BTS or the MRT (theo-courant, 2022). The second route is The Khlong Saen Saeb electric boat service, offering a free 11-km journey during the demonstration period between Wat Sriboonruang pier and the Min Buri district office pier (NNT, 2023).

Figure 23: Electric boat service in Bangkok

According to Chavanaves (2021), in Figure 24, Scenario 2 (electric car sales gradually make up 50% of all new vehicles registered in 2024 and remain at this proportion onwards until 2029) and Scenario 3 (all Bangkok Mass Transit Authority (BMTA) public buses are changed to electric vehicles in the year 2022) show a small reduction in $PM_{2.5}$ emissions. This may come as a surprise, as the increase in the proportion of electric vehicles was calculated to have little effect on total $PM_{2.5}$ emissions (6.15% reduction for Scenario 2 and 0.73% for Scenario 3). This is because, despite the increase in electric vehicles, the BMR vehicle fleet would still be comprised of a large number of older vehicles running on fossil fuels. Moreover, in Scenario 2, pick-ups and trucks were not affected. However, they happened to be the top two biggest emitters of $PM_{2.5}$, as shown by the colors of the chart in Figure 24. Pick-ups and trucks are mostly diesel-powered with high emissions, while the electric passenger cars and electric motorcycles expected to be added to the fleet are reducing emissions from sources that already have low emissions since the beginning. For Scenario 3, replacing BMTA public buses with e-buses would affect only around 13,000 buses, while the total bus fleet in BMR consists of more than 50,000 buses, thus resulting in an insignificant reduction in total emissions.

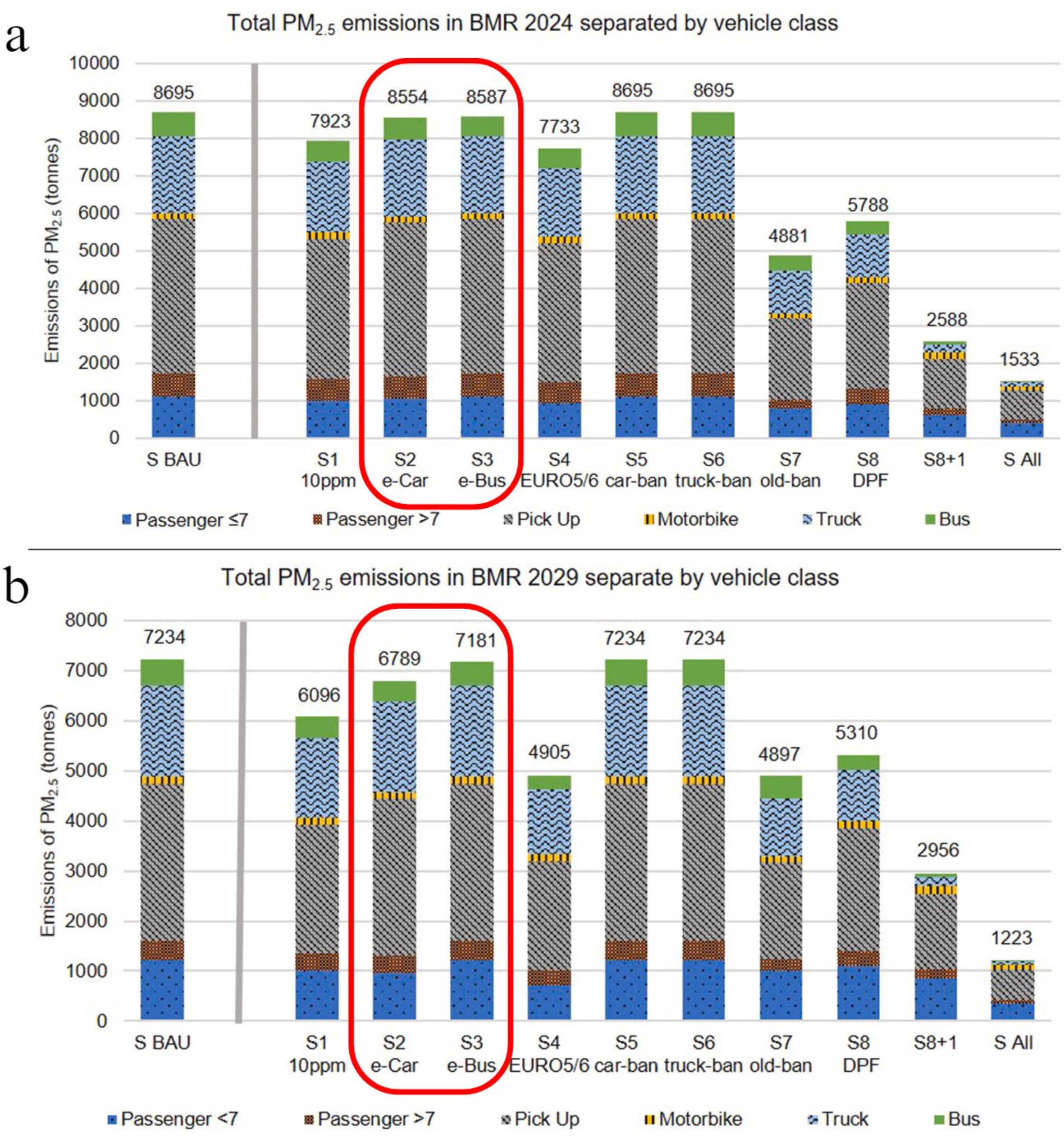

Figure 24: Prediction of $PM_{2.5}$ emission if EV technology is used in Thailand: a) 2024 and b) 2029 *(Chavanaves et al., 2021)*

Advantages of electric vehicles are as follows:

- Electric vehicles utilize 100% electrical energy for propulsion, which helps save on expenses for both maintenance and electricity. In general, electricity costs less than fuel, and importantly, electric vehicles produce zero exhaust emissions, making them environmentally friendly (Suwanthada P. et al., 2022).
- Electric vehicles have various advantages, including fewer GHG emissions, safety, cost savings, and low maintenance, and offer a long-term solution to environmental concerns (Kongklaew et al., 2021).
- Electric vehicles can provide sustainable transportation (Kongklaew et al., 2021).

- Electric vehicles have the potential to reduce reliance on fossil fuels (Kongklaew et al., 2021).
- EVs have advantages in fuel and maintenance costs. The fuel cost of EVs comes from electricity, which is less expensive and produces fewer direct emissions compared to gasoline-fueled vehicles. However, this is highly dependent on how electricity is produced in each country. EV maintenance cost is also less than that of ICEVs due to the reduced complexity of EV motors (Kongklaew et al., 2021).

Disadvantages of Electric vehicles are as follows:

- EVs will mainly replace new vehicles, which will not affect the highest portion of emission-generated vehicles (old diesel vehicles). Other policies/technologies to tackle older vehicles on the road should be implemented together. Thailand's tax on older vehicles being higher than that on newer ones should also be used (Marks, 2020).
- Thailand still has a fledgling electric vehicle market, unlike Europe, China, and other places. Thus, there is limited charging infrastructure and insufficient financial incentives to promote buying electric vehicles, which are much cleaner than other vehicles (Marks, 2020).
- Current proposed recommendations are often distant from reality and not feasible in the short to medium term timeframe. For example, one recommendation sets an electric car sales target of 50% of all new vehicles registered in 2024. However, in 2021, only 3.8% of new vehicle registrations in Bangkok were hybrid electric cars, with a mere 0.5% being fully electric (DLT, 2021).
- The high costs of EVs and batteries are major barriers in many consumer surveys (Kongklaew et al., 2021).
- EV performance and range are key barriers to their adoption. Drivers cannot estimate how far they could go or extend a journey based on the remaining battery. Other unsatisfying EV performance issues include charging time (Kongklaew et al., 2021).
- The battery replacement cost is approximately THB 250,000–400,000 (Kongklaew et al., 2021).

5. Continuous Emission Monitoring Systems (CEMS) for industrial air pollution control

A continuous emission monitoring system (CEMS) is the set of equipment necessary for the measurement of gas or particulate matter concentration or emission rate using pollutant analyzer measurements and a conversion equation, graph, or computer program to produce results in units of the applicable emission limitation or standard (USEPA, 2023). According to the CEMS cost data collected by Chevron and Stone and Webster Engineering Corporation, the initial direct cost of CEMS is 195,000 USD, and the initial indirect cost is 171,000 USD. Hence, the total installation cost is 366,000 USD. The yearly operating cost is 27,000 USD (Chien et al., 2003). CEMS components (Figure 25) consist of:

1. A sampling system, which is a device installed at the exhaust stack to measure particulate matter.
2. Analyzer, a system that measures air pollutants (CO, NOX, SO_2, O_2) using CEMs analyzers, which receive data from the particulate matter measurement tool for analysis.
3. Data acquisition, which collects and stores analyzed data in a computer system. The analyzed data are then transmitted to the air quality monitoring system, which includes the following (for the case of Thailand):
    - Factories located inside the Industrial Estate area shall submit emission monitoring data to the IEAT Data Center (Environmental Monitoring & Control Center: EMCC).
    - Factories located outside the Industrial Estate area shall submit emission monitoring data to the DIW Data Center (Industrial Environmental Monitoring Center: IEMC).

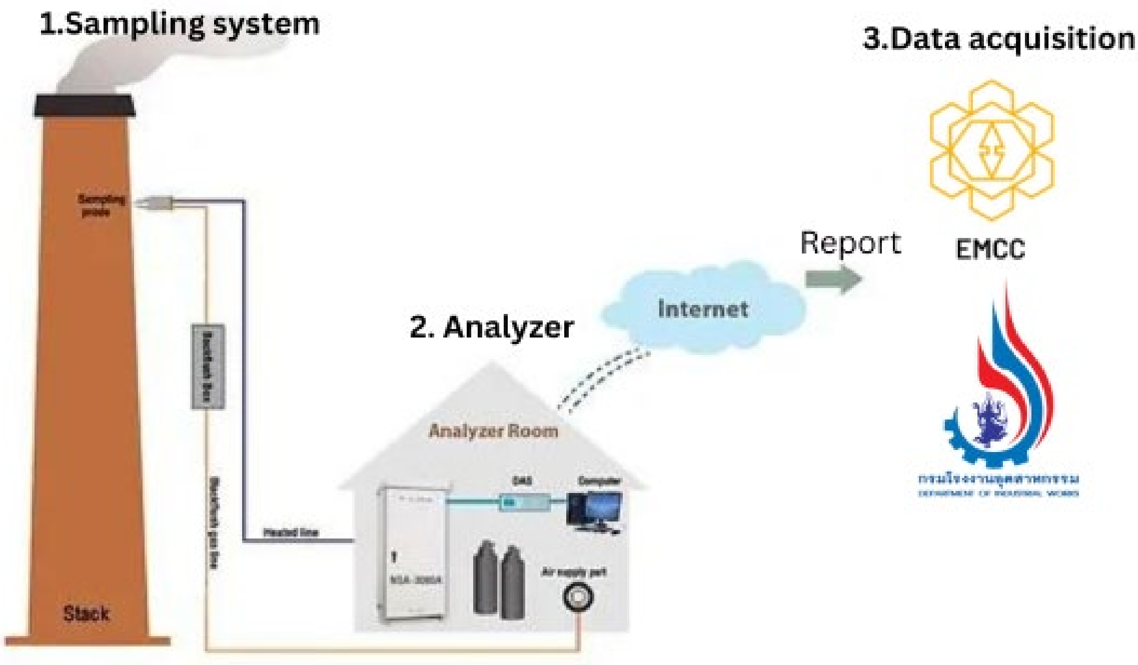

Figure 25: Component of CEMs

For the implementation of CEMs in Thailand, the Ministry of Industry addressed the air quality issue in the Mab Ta Phut area of Rayong Province by issuing a notification in 2001. This notification required environmentally high-risk factories located in four industrial estates in Mab Ta Phut Sub-district to install Continuous Emission Monitoring Systems (CEMS). The industrial estates included Mab Ta Phut Industrial Estate, Pha Daeng Industrial Estate, Eastern Seaboard Industrial Estate (now WHA Eastern IE), and Asia Industrial Estate. Then, in 2007, the Department of Industrial Works established a data center and mandated factories to transmit their CEMS data to this central facility. Subsequently, in 2010, the Industrial Estate Authority of Thailand (IEAT) extended the requirement to all power plants situated in industrial estates across the country, ordering them to install CEMS and submit their data to the Environmental Monitoring and Control Center (EMCC) (Leungsakul S., 2021).

Currently, as part of the National Agenda for action plans “Solving the dust pollution problem” in Thailand for the period 2019-2024, one of the strategies is controlling and reducing pollution from industrial sectors. The approach to implementation is installing Continuous Emission Monitoring Systems (CEMS) that continuously monitor and report emission data from the exhaust stacks of the industries in Category 3 (a factory of a category, type, and size that may be established only after a license has been issued). Then, the data will be reported online to the Ministry of Industry (PCD, 2019). This implementation is in correlation with the regulations issued by the Ministry of Industry (MOI), which require different categories of factories to install Continuous Emission Monitoring Systems (CEMS). These requirements primarily apply to large-scale factories such as power plants and oil refineries aimed at improving the quality of emissions. MOI has also required additional parameters in the report, i.e., oxygen concentration and temperature. Moreover, CEMS equipment must undergo periodic calibration and verification as specified by the regulations issued by the Ministry of Industry effective date on 11 June 2023 (MOI, 2022), as shown in Table 5.

Table 5: The amount of industry in Bangkok *(MOI, 2022)*

Category of the industry	Number of factories
Type 1 factory is defined as a facility with all equipment installed, not exceeding 20 HP (horsepower) or its equivalent, and employing no more than 20 individuals. It is exempt from being classified as a factory under the law in the future.	9
Factory Type 2 is a facility with all equipment installed, not exceeding 75 HP (horsepower) or its equivalent, and employing no more than 75 individuals. Approval from the Ministry of Industry (MOI) is not required before establishing the factory. However, it must not fall under the category of emission pollution and should not have an adverse effect on the environment.	693
Factory type 3 is a facility with all equipment installed using energy of more than 75 HP (horsepower) or having more than 75 employees. Additionally, approval from the Ministry of Industry (MOI) is necessary before establishing the factory.	4883

Table 6: Factory type that requests to install CEMs *(MOI, 2022)*

Code of Factory Type	Size and production capacity per day	Number of factories
38	Production units of pulp and paper with a production capacity exceeding 50 tons per day.	1
42	Production units of sulfuric acid with a production capacity exceeding 100 tons per day, excluding those specifically designated for packaging.	14
49	Production units of petroleum distillation at any production capacity.	1
54	Production units of glass manufacturing, glass fiber production, or glass products utilizing a furnace with a heat input exceeding 100 MMBTU per hour, excluding heat from Electric Booster systems and Heat Recovery.	4
57	Production units of cement with a production capacity exceeding 3,000 tons per day.	4
59	Production units of steel involving smelting, casting, rolling, or producing, with a combined production capacity exceeding 100 tons per day.	22
60	Production units of non-steel involving smelting, casting, rolling, or producing, with a combined production capacity exceeding 50 tons per day.	38
88 (2)	Production units of electricity and heat with a production capacity exceeding 10MW.	13
101	Central waste treatment plant.	7

Table 7: The emission factor of pollutants from industrial sources (kg-pollutant/hp-industry) *(Winijkut et al., 2023)*

Code of Factory Type	Size and production capacity per day	$PM_{2.5}$	PM_{10}	SO_2	CO_2	CO	NOx	NH_3	CH_4	NMVOC
38	Production units of pulp and paper with a production capacity exceeding 50 tons per day.	4.3513	6.2162	18.9029	1860.4107	0.1715	6.1267	0.0037	0.1116	0.0261
42	Production units of sulfuric acid with a production capacity exceeding 100 tons per day, excluding those specifically designated for packaging.	0.0276	0.0394	0.5272	87.8921	0.3131	1.1053	0.0026	0.0063	0.0556
49	Production units of petroleum distillation at any production capacity.	2.4857	3.5510	6.4346	87.8921	0.7533	4.3379	0.0026	0.0063	0.1185
54	Production units of glass manufacturing, glass fiber production, or glass products utilizing a furnace with a heat input exceeding 100 MMBTU per hour, excluding heat from Electric Booster systems and Heat Recovery.	0.2176	0.3108	4.0744	2008.5021	1.9640	7.3343	0.0042	0.2187	0.3514
57	Production units of cement with a production capacity exceeding 3,000 tons per day.	14.8399	21.1999	27.3738	2008.5021	0.2759	8.3049	0.0042	0.2187	0.0417
59	Production units of steel involving smelting, casting, rolling, or producing, with a combined production capacity exceeding 100 tons per day.	0.0133	0.0189	0.2390	77.1313	0.1481	0.5358	0.0017	0.0044	0.0266
60	Production units of non-steel involving smelting, casting, rolling, or producing, with a combined production capacity exceeding 50 tons per day.	0.0367	0.0524	0.1811	77.1313	0.2170	0.9213	0.0017	0.0044	0.0624
88 (2)	Production units of electricity and heat with a production capacity exceeding 10MW.	-	-	-	-	-	-	-	-	-
101	Central waste treatment plant.	0.2187	0.3124	4.2745	12.4357	1.0735	5.2119	0.0001	0.0005	0.1732

The database from the Department of Industrial Works (as of December 1, 2022) identified 24,690 factories in the Bangkok Metropolitan Region and 5,639 factories in Bangkok (PCD, 2022). Furthermore, in line with the Ad Hoc Plan on Solving the Dust Pollution Problem in Bangkok 2023, enforcement efforts have been heightened during Phase 2 when the $PM_{2.5}$ concentration reaches a crisis level (37.6-50 $\mu g/m^3$). The Bangkok Metropolitan Administration (BMA) will conduct inspections on 260 factories in the Bangkok area that have a high potential to emit pollutants. If these factories exceed the emission standards, they will be given a specified time to address the issues. Failure to comply with the required improvements may lead to the factories being ordered to cease operations under the Factory Act of 1992 (BMA, 2022).

Advantages of CEMs are as follows:

- Real-time 24-hour reporting or having emission data from factories for more than 80% of operating hours.
- High potential for successful implementation in the country due to supportive laws, environmental impact assessments (EIA), and factory permit conditions.
- Widely used in over 60 countries with more than 560 successful projects and over 30 years of operational knowledge (Siemens Energy, 2023).
- Self-monitoring for process optimization and early warning (Leungsakul S., 2021).
- Providing better compliance with emission standards (Leungsakul S., 2021).
- Reducing pressure from the community through information disclosure (Leungsakul S., 2021).
- Gaining trust from the community and increasing communication effectiveness (Leungsakul S., 2021).

Disadvantages of CEMs are as follows:

- Only applicable to large-scale factories; the Ministry of Industry (MOI) requires only the industrial sector in category 3 to install Continuous Emission Monitoring Systems (CEMS). It is estimated that only 104 factories, or around 1.9% of all factories in the Bangkok area, must install CEMs (Figure *26*).
- CEMs can only control emission sources from the industrial sector.
- Not all factories with CEMs installed are required to report PM. According to the note:
  - **i.** Natural gas (NG), liquefied petroleum gas (LPG), and hydrogen gas (H_2) fuels are not required to measure sulfur dioxide (SO_2) and particulate matter.
  - **ii.** Gas fuels are not required to measure particulate matter.
- Particulate matter is reported in terms of fine particulate matter (mg/m^3) but does not specify $PM_{2.5}$.

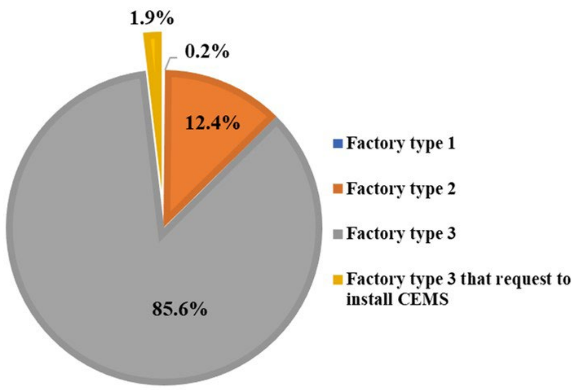

Figure 26: Percentage of factories in Bangkok that must install CEMs (https://www.diw.go.th/webdiw/search-factory/)

6. Cleaner cooking (cleaner fuel and cleaner stove), including street food

Solid fuels, including dung, coal, wood, and agricultural residues, are utilized by approximately half of the world's population for cooking and heating. The combustion of these fuels in open fires or inadequate stoves releases harmful pollutants into the household atmosphere, as depicted in Figure 27 (Thomas et al., 2015). Consequently, the Climate and Clean Air Coalition (CCAC, 2019) presents air pollution measures for Asia and the Pacific, featuring 25 science-based solutions to promote clean and safe air. Two of these solutions are geared toward controlling air pollution in the residential sector.

The first solution advocates for clean cooking and heating. CCAC recommends the use of clean fuels in households, such as electricity, natural gas, and Liquefied Petroleum Gas (LPG). For rural areas, CCAC suggests employing LPG, advanced biomass cooking, and heating stoves as substitutes for coal (Zusman et al., 2019). Furthermore, Figure 27 illustrates that gases and LPG are alternative energy sources that can help reduce particulate matter (PM) emissions (Shrestha et al., 2013).

The second solution involves energy efficiency for households. CCAC encourages the installation of rooftop solar panels to enhance the energy efficiency of household appliances, buildings, lighting, heating, and cooking (Zusman et al., 2019). Regarding the cost of cleaner cooking, the expense of a clean cooking stove is estimated to range from 2 USD per stove to over 100 USD per stove, depending on the technology and thermal efficiency characteristics of the stove (Filmanovic M.E. , 2023).

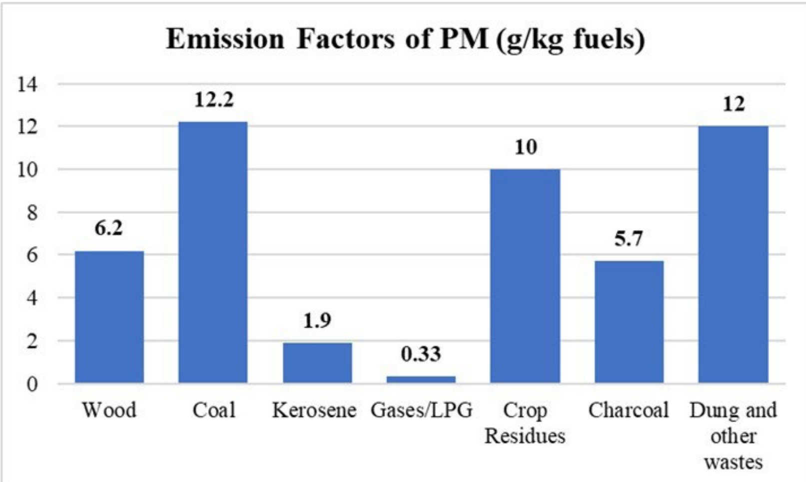

Figure 27: Emission Factors of PM from various materials in the residential sector *(Shrestha et al., 2013)*

China and India have implemented cookstove programs aimed at providing cleaner stoves for users. In China, government agencies collaborated on the National Improved Stove Program (NISP) with the goal of supplying cleaner stoves to 129 million households, covering approximately 65 percent of China's population. Similarly, India has introduced several cookstove programs to address the needs of approximately 100 million households (out of 240 million) that lack access to modern cooking options.

In Thailand, the household energy consumption rate constituted approximately 15% of all sectors in 2010 (Ministry of Energy, 2011), as illustrated in Figure 28. Thailand's primary energy sources encompass coal and coal products, biofuels and waste, electricity, oil products, natural gas, crude, Natural Gas Liquids (NGL), and feedstocks. An analysis of energy consumption in the household sector revealed that over half of it is derived from biofuels and waste, followed by electricity and oil products, as indicated in and Figure 29 and 30 (IEA, 2018). A study on $PM_{2.5}$ emission inventory in Bangkok disclosed that 12% of $PM_{2.5}$ originated from the residential sector (household, street food, and market) (Winijkut et al., 2020).

As part of the National Agenda for action plans to “Solve the dust pollution problem” in Thailand for the period 2019-2024, the country has implemented measures for the prevention and reduction of pollution at the source. One of the strategies involves controlling and reducing pollution from the household sector by promoting the use of clean energy in households and developing and endorsing pollution-free cooking and grilling stoves (PCD, 2019).

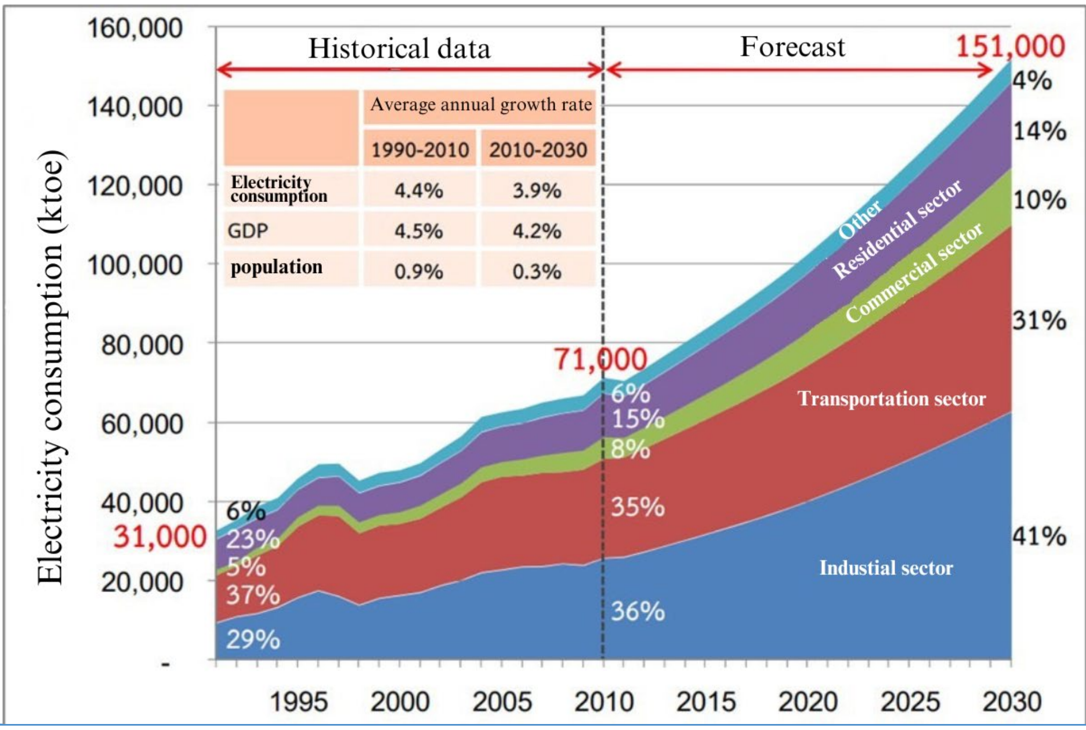

Figure 28: Trend of electricity consumption in Thailand *(Ministry of Energy , 2011)*

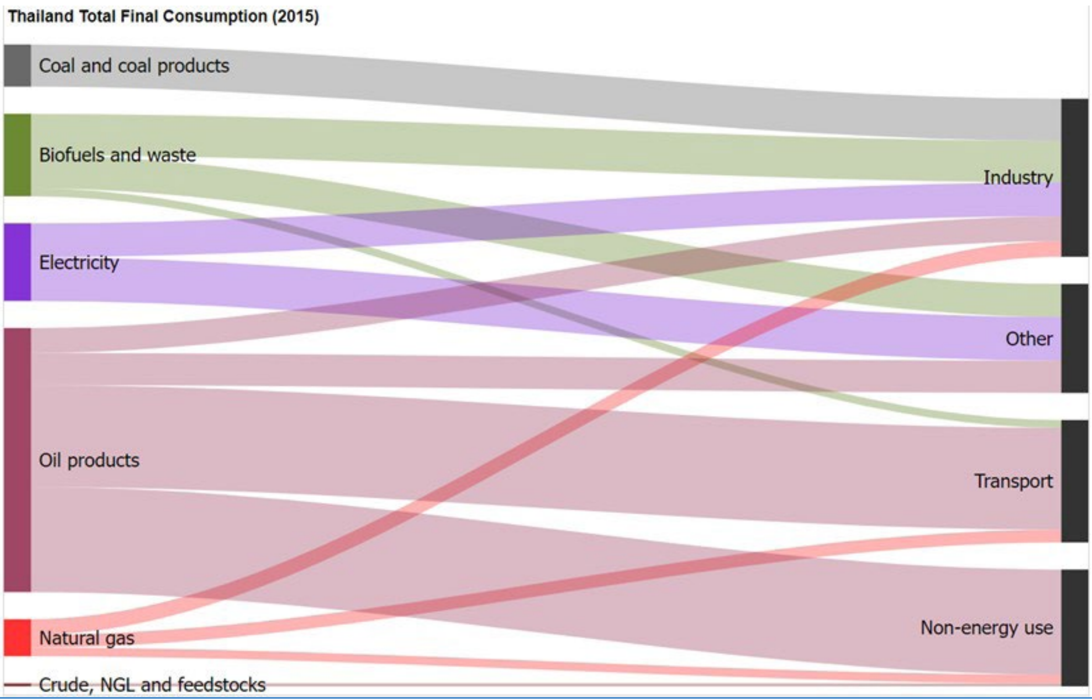

Figure 29: Main fuels source of energy consumption from all sectors of Thailand *(IEA, 2018)*

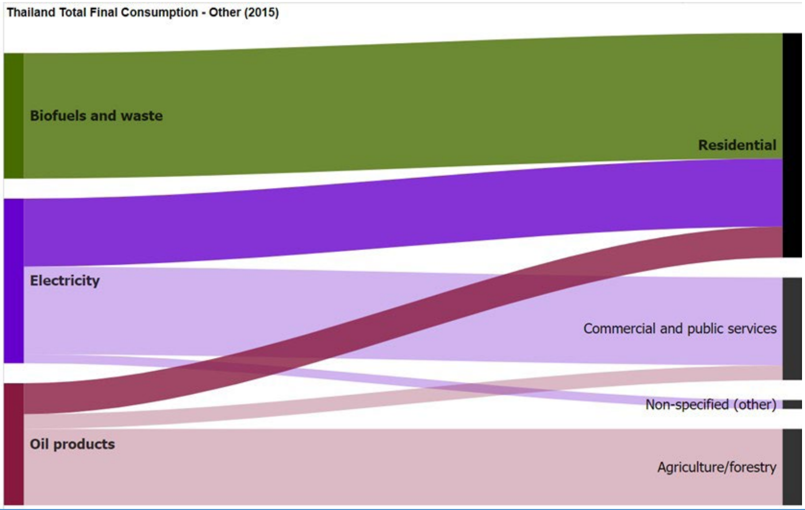

Figure 30: Main fuels in residential sectors of Thailand *(IEA, 2018)*

Table 8: The data on fuel consumption in different activities for markets and street food in the Bangkok metropolitan area *(Winijkut et al., 2023)*.

Province	Grilling (kg/Shop-Day)		Boiled/steamed/stir-fried/fried/etc. (kg/Shop-Day)	
	Wood/Coal	LPG	Wood/Coal	LPG
Bangkok	6.0	3.6	12.9	4.8
Nakhon Pathom	4.7	3.4	5.0	3.0
Nonthaburi	5.4	3.4	4.7	4.3
Pathum Thani	7.2	1.9	6.4	1.7
Samut Prakan	5.6	2.7	3.0	4.0
Samut Sakhon	4.7	4.1	6.4	4.1

Table 9: Activity data on the proportion of cooking for markets and street food *(Winijkut et al., 2023)*

Province	Source of Pollution	Use Fuel %		Non-use fuel %
		Grilling	Boiled/steamed/ stir-fried /fried/etc.	Other product
Bangkok	markets	19.7	46.2	34.2
	street food	19.7	41.7	38.6
Nakhon Pathom	markets	15.6	50.7	33.7
	street food	23.1	38.5	38.5
Nonthaburi	markets	14.0	50.1	35.8
	street food	27.3	42.7	30.0

Table 9: *(Continued)*

Province	Source of Pollution	Use Fuel %		Non-use fuel %
		Grilling	Boiled/steamed/ stir-fried /fried/etc.	Other product
Pathum Thani	markets	16.8	48.3	34.9
	street food	23.4	40.9	35.7
Samut Prakan	markets	16.5	44.7	38.8
	street food	23.4	40.9	35.7
Samut Sakhon	markets	16.9	50.6	32.5
	street food	23.4	40.9	35.7

Advantages of cleaner cooking are as follows:

- More modern stoves are highly efficient and can reduce fuel use by 30%-60% (CCA, 2023).
- Recent evidence also demonstrates that the most advanced (efficient and low-emission) cookstoves and fuels can reduce black carbon emissions by 50%-90% (CCA, 2023).
- Switching to clean cooking—using modern stoves and fuels—transforms lives by improving health, protecting the climate and the environment, and helping consumers save time and money (CCA, 2023).
- Bhattacharya and Salam (2002) estimated that switching to biofuel, biogas, and gasifier stoves could provide 38–61% reductions in greenhouse gas emissions compared with traditional stoves used in Asian countries.
- Grieshop et al. (2011) found that replacing traditional stoves with kerosene, LPG stoves, and improved stoves with fans could provide benefits to indoor health and the global climate (Grieshop et al., 2011).
- UNEP (2011), based on GAINS emission inventories, estimated that reducing black carbon through improved biomass stoves or switching to cleaner-burning fuels would deliver the greatest health and near-term climate benefits, compared with improving transportation, banning open burning of agricultural waste, or providing modern brick kilns and coke ovens.
- A clean-fuel scenario reduces emissions by 18–25%, depending on the pollutant, while stove improvements with existing technology reduce emissions by 25–82% (Winijkul et al., 2016).
- If stoves meet the tightest performance standards, particulate matter is reduced by 95% (Winijkul et al., 2016).

Disadvantages of cleaner cooking are as follows:

The most significant and challenging aspect confronting the renewed movement for clean cooking is whether and how people will adopt this new generation of technologies. Cooking is a culturally bound practice that is highly attuned to very local, current, and historical socioeconomic contexts. Many cookstove programs and experimental failures likely occurred at the interface between a family's needs and the availability of clean, inexpensive, durable, and easily used cookstoves and fuels (Rosenthal, 2015). Additionally, numerous factors influence the energy consumption of households, such as the physical and structural aspects of households, social support, and economic factors, including communication and information (Sirichotpundit et al., 2013).

7. Applications help to manage agricultural wastes (not to burn)

Applications that can assist in managing agricultural waste can be utilized for registering and permitting the burning of agricultural waste, including reporting fire incidents. In Thailand, these applications are available in two main apps:

Burn Check (Figure 31): Burn Check, an application developed by GISTDA, serves as a tool for citizens to register and obtain permits for burning agricultural wastes. The local administration approves these permits through an automated system. Users can submit burn permit requests by providing location coordinates, burning area size, purpose of burning, and images of the area before burning. The system administrator evaluates and approves the burning request. If the request is not approved, the app provides reasons, such as a high number of burning requests on the requested date, which may lead to a higher $PM_{2.5}$ concentration than the standard. In such cases, users are advised to reschedule burning activities. The application also offers advice and alternative ways to manage agricultural residuals, promoting the development of new products or assisting farmers in selling agricultural waste directly to business owners. The main feature of this application is its ability to control the quantity of burning points in specific areas (Doungthai T., 2021; Haze Free Thailand, 2021). The estimated cost for this project was 3,500,000 Baht (98,398 USD), covering supporting activities such as the development of the Burn Check application platform, data preparation and analysis for system input, project promotion, publicizing, training, and promoting the use of the decision support system for Burn Check in the 17 participating provinces (GISTDA, 2021).

Fire D (Figure 32): Fire D is an application designed for community data collection to support decision-making in agriculture burning at appropriate times. The system in the application can be separated into two parts. The first part is the registration section for normal users or officials involved in fire management to submit permits for burning agricultural waste requests to local authorities. This part requires users to fill in the information in the app, such as smoke types, fire types, and the size of the fire management area. The second part is the decision-making section, where data from air quality measurements, hotspot information, and meteorological data are considered. After the registration requests are received, the Forest Fire Control and Prevention Command Center evaluates and approves them using the WRF-Chem model. The advanced air quality prediction process takes an estimated 3-5 days and is evaluated with other factor conditions for decision-making before approval (Doungthai T., 2021). The criteria for approval are as follows:

1. $PM_{2.5}$ concentration must not exceed 50 $\mu g/m^3$ on the requested burning date.
2. Air dispersion and wind stream must be favorable on the requested burning date.
3. Burning activities are allowed only between 11:00-16:00 hrs.

In Chiang Mai province, the Fire D app has been employed to address haze and forest fire issues, successfully reducing hotspots by 60% and burned areas by 50%. However, the application serves as a tool to help manage fires, and lessons learned and practical experiences have been shared through deep discussions and operational meetings involving volunteers, village leaders, and subdistrict heads to develop fire management plans in Chiang Mai Province (Greennews, 2021; Doungthai T., 2021; Haze Free Thailand, 2021).

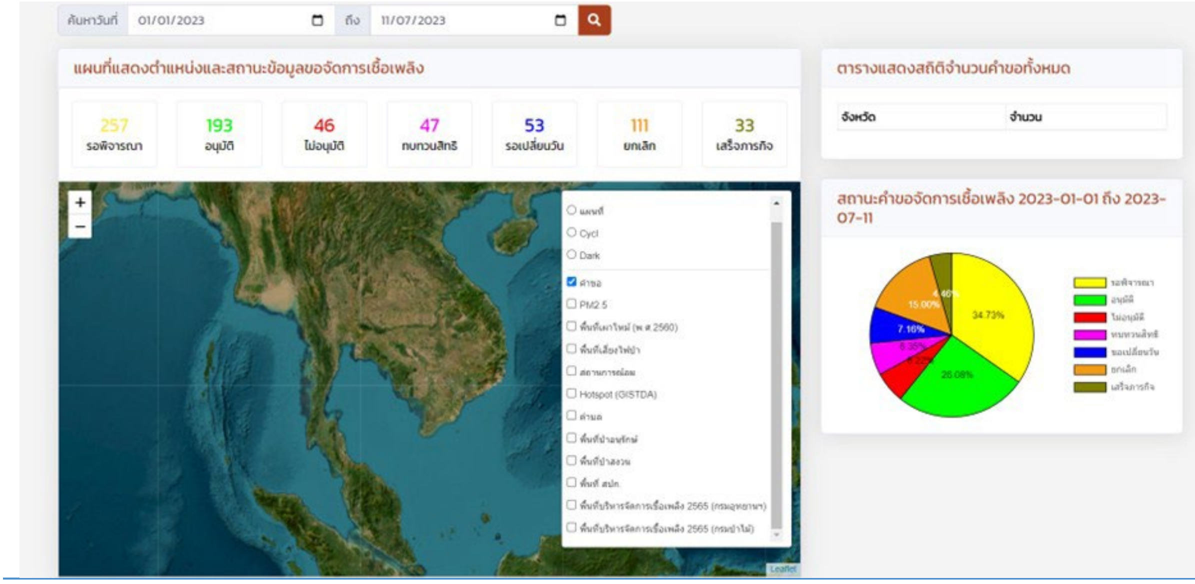

Figure 31: Burn check application (http://www.burncheck.com/public)

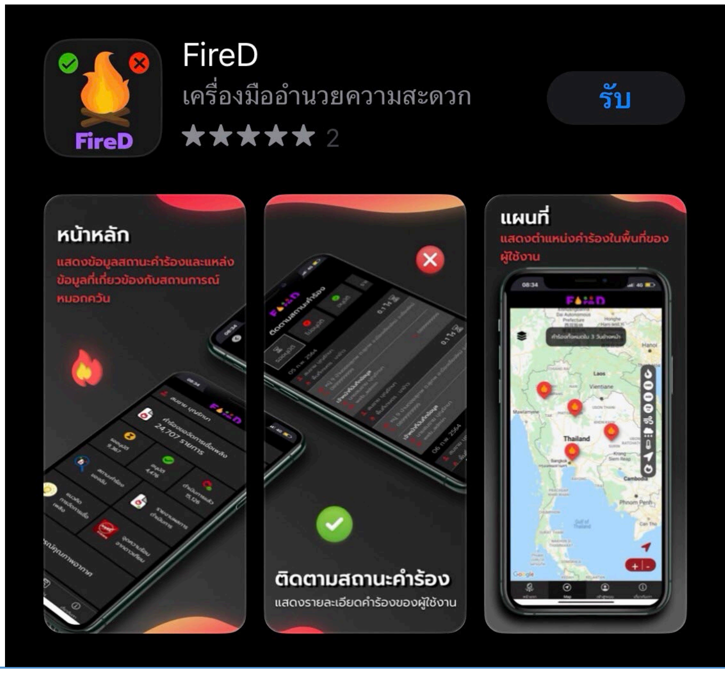

Figure 32: Fire D application

As part of the Ad Hoc Plan for Solving the Dust Pollution Problem in Bangkok 2023, measures have been implemented to control open burning activities. When the $PM_{2.5}$ concentration is at level 1 (less than 37.5 µg/m^3), monitoring and a 100% ban on burning agricultural waste activities will be in effect in the Nong Chok District, Khlong Sam Wa district, and Lat Krabang district. The control measures will be stricter when the $PM_{2.5}$ concentration reaches level 2 (more than 37.5 µg/m^3). At this level, agricultural open burning will be completely banned in the Bangkok Metropolitan Region, and strict enforcement of the law will be implemented against violators (BMA, 2022). However, this may lead to increased burning before and after the policy announcement (during the banning period).

Advantages of these Application are as follows:

- Applications help collect statistics and data for retrospective studies on trends and causes of forest fires, including geolocation data (providing coordinates in both latitude, longitude, and UTM units).
- Forest fire mapping provides insights into causes and is beneficial for developing prevention and mitigation methods.
- Permits for agricultural burning help manage and prevent the dispersion of $PM_{2.5}$ higher than the standard during periods of high pollution.
- Providing convenience for users to register permits for burning agricultural waste and enabling simultaneous evaluation of multiple pollution sources, reducing the burden on local officials (registration can also be done in person at local offices if online registration is inconvenient).
- Easily check the burning process because users can upload images before and after burning agricultural waste.
- Users must provide information on the quantity of firewood in the registration form, which data may be beneficial for commercial purposes.

Disadvantages of these Application are as follows:

- Applications helping to manage air pollution from the agricultural sector are a pilot project used in some provinces in Thailand and need more collaboration to expand to other areas.
- Lack of policies to support registering permits through the applications before burning agricultural waste.
- It does not reduce $PM_{2.5}$ emissions but only limits emissions during periods of high $PM_{2.5}$ concentration.
- Lack of alternative measures in case burning is not permitted. The government should assist in managing agricultural waste, such as purchasing it for biofuel.
- Applications that help manage air pollution from the agricultural sector have not gained popularity among the Thai public, which may be due to 1) insufficient public awareness and promotion of the apps, 2) lack of training on app usage for the target audience, 3) using academic language that is hard to understand by the target audience, and 4) resistance to adopting new technologies.

8. Satellite detection for agricultural open-burning control

Fires should be a concern, particularly in areas with longer fire seasons, expanded interfaces between wildland and urban regions, and frequent and severe droughts. Both anthropogenic-caused and naturally occurring fires have significant impact on vegetation, soil properties, atmospheric chemistry, and the overall landscape. Anthropogenic fires are often intentionally set to clear grasslands and agricultural areas before the planting season, while forests may be cleared using fires to repurpose the land for other uses.

Remote sensing techniques, such as satellite-based observations, play a vital role in monitoring various aspects related to fires, including pre-, during-, and post-fire conditions. Remote sensing enables the monitoring of weather and climate conditions, pollutant concentration (Figure 33), fuel characterization, fire risk assessment, smoke detection, fire behavior analysis, and post-fire landscape evaluation (NASA, 2021). Earth observation (EO) satellite data available from the U.S. National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) are being used to develop the Global Fire Map (Jessica M., 2017). This map utilizes heat points derived from satellite sensors that detect abnormal levels of heat on the Earth's surface compared to the surrounding areas. Each sensor model has its own pixel size or resolution, and the reported values are usually the average pixel value, even though there may be multiple groups of pixels within a specific area, as shown in Table 10 (Channarong J. et al., 2022). Currently, two satellite models, namely the Moderate Resolution Imaging Spectroradiometer (MODIS, Figure 34), and the

Visible Infrared Imaging Spectrometer Suite (VIIRS, Figure 35), are used to map all fires worldwide (Jessica M., 2017). Although there are some other satellites (e.g., Himawari) used for fire detection, the spatial resolution is not as great as MODIS and VIIRS.

Moreover, the Geostationary Environment Monitoring Spectrometer (GEMS), is an instrument installed on the KOMPSAT-2B satellite, a satellite of South Korea. It is another satellite that uses remote sensing techniques to help in monitoring the quantities of gases and particulate matter (PM_{10} and $PM_{2.5}$) affecting our Earth's environment continuously. These gases include nitrogen dioxide, sulfur dioxide, and formaldehyde. Thailand utilizes data from the GEMS sensor to enhance the efficiency of air pollution management, in conjunction with information from the MODIS system (Terra and Aqua satellites), VIIRS system (Suomi-NPP satellite), Himawari satellite, and other satellites. Ground-based monitoring devices are set to be installed in Bangkok, Pathum Thani, Chiang Mai, and Songkhla in 2021 (NIER, 2020; Kim et al. , 2020; GISTDA, 2021).

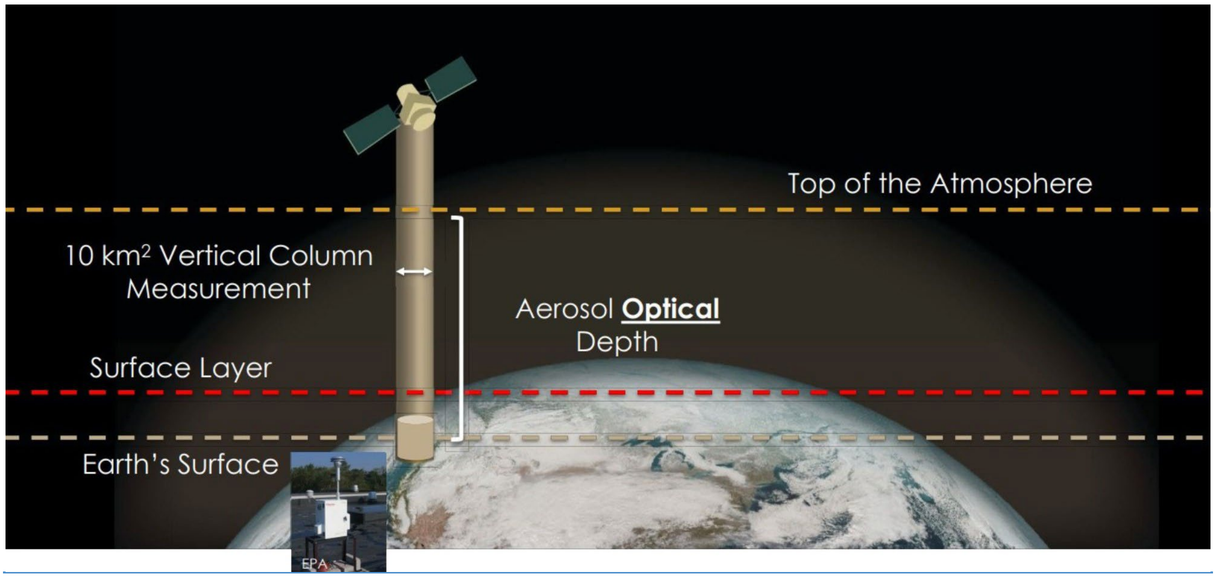

Figure 33: Satellite detection concept for Aerosol Optical Depth (AOD)

Table 10: Detail of satellite sensing for detecting hotspots in Thailand *(Channarong J. et al., 2022)*

Sensor	Satellite	Year of satellite operation	Spatial Resolution per pixel	Time that the satellite passed Thailand	The smallest size of the hotspot that it can detect
MODIS	Terra	1999	1000×1000 m	09:30-12:00 21:30-24:00	2,500 m²
	Aqua			12:30-15:00 00:30-03:00	
VIIRS	Suomi NPP	2011	375×375 m	12:30-15:00 00:30-03:00	4 m²
	NOAA-20			12:30-15:00 00:30-03:00	
GEMS	KOMPSAT-2	2021	7×8 km (gas) 3.5×8 (aerosol)	9:45–11.45	NA

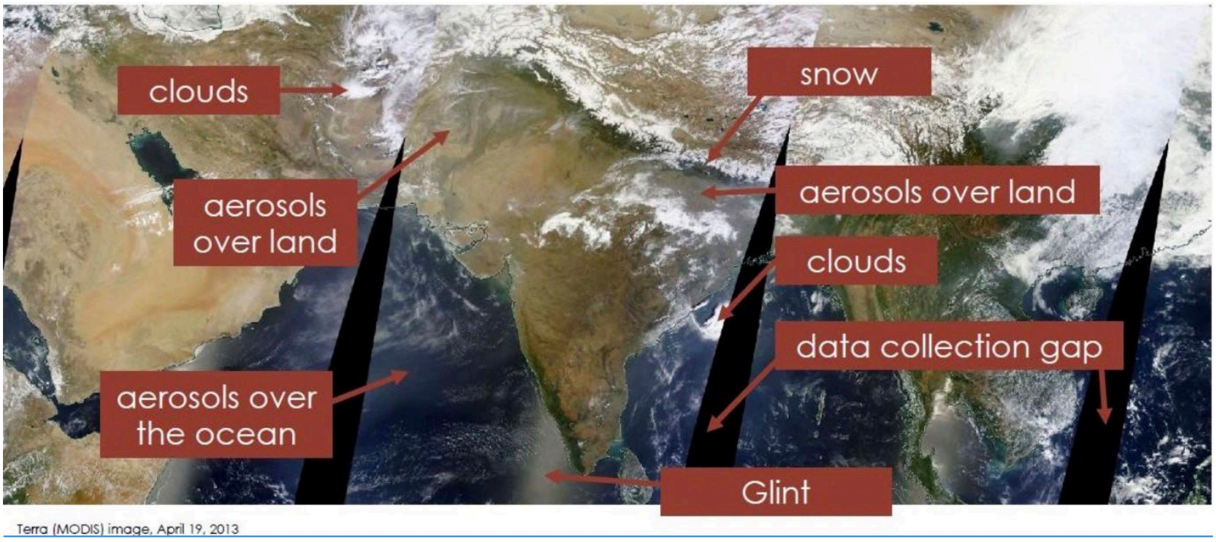

Figure 34: Visible Smoke from Fires detected by MODIS *(Prof. Muhammad Bilal , 2021)*

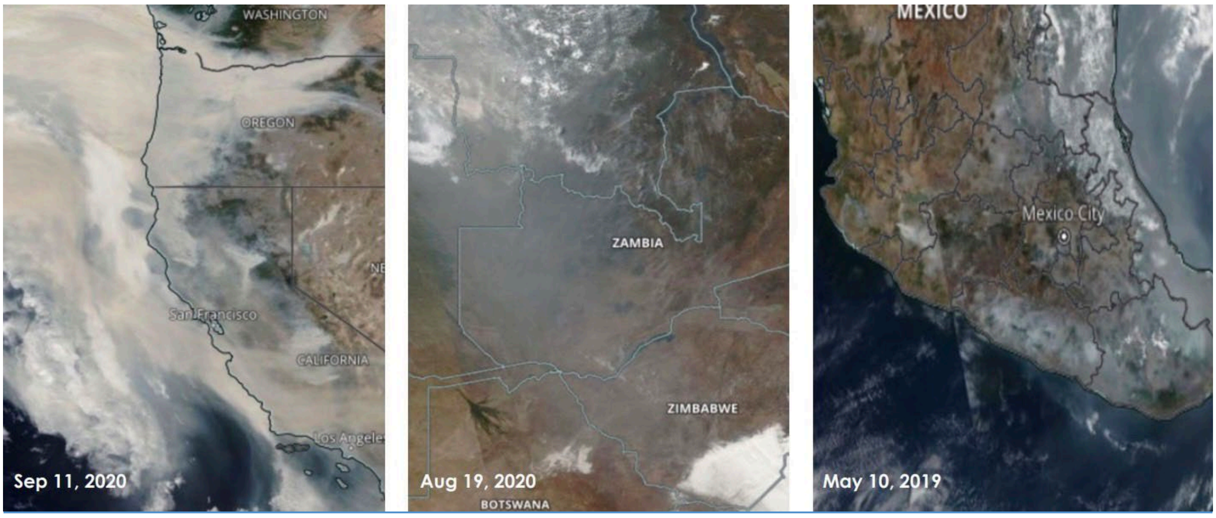

Figure 35: Visible Smoke from Fires detect by VIIRS (NASA's Applied Remote Sensing Training Program, 2021)

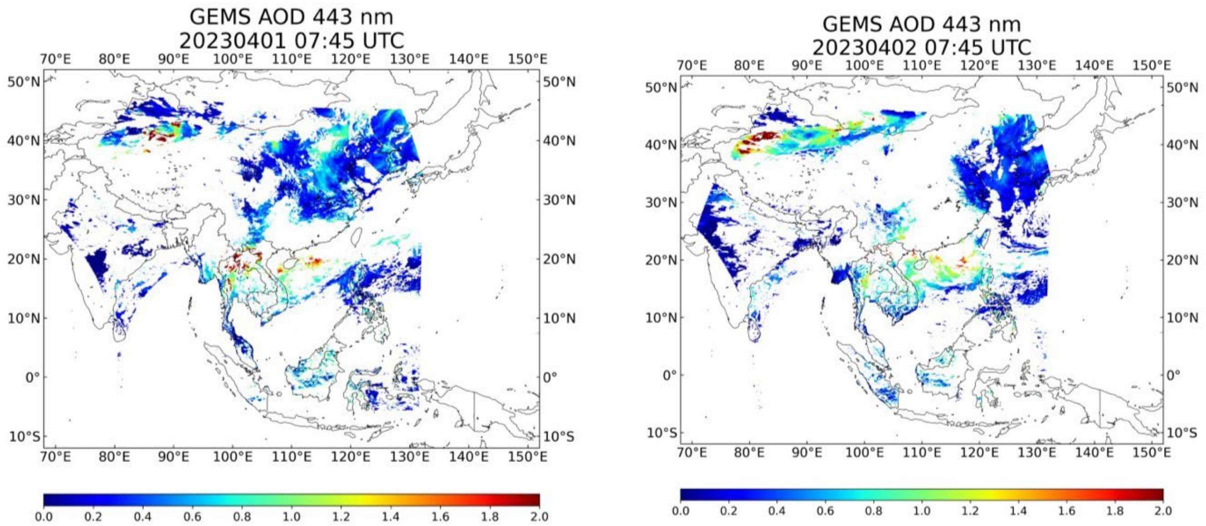

Figure 36: GEMS Mapping Air Pollution (*https://nesc.nier.go.kr/en/html/satellite/viewer/index.do*)

In Thailand, the Geo-Informatics and Space Technology Development Agency (GISTDA) is primarily responsible for receiving satellite signals, analyzing data, and disseminating it to government agencies and the public. GISTDA provides data services through the website https://fire.gistda.or.th/. The website publishes nationwide hotspot data during satellite passes and provides daily summarized data in the form of maps (Figure 37) and tables at the provincial and district levels. It also offers daily services for mapping the distribution of haze and wind directions throughout the country. Most government agencies rely on the hotspot data processed by GISTDA for their operations. The cost of this project was estimated at 5,295,000 Baht (148,862 USD) (GISTDA, 2021) for supporting activities as follows:

- Creating a satellite database with the potential to provide $PM_{2.5}$ data and satellites that provide physical-related factors affecting and influencing $PM_{2.5}$ concentration, consisting of one platform of databases from the MODIS satellite system and the Himawari-8 satellite system, covering the territory of Thailand and neighboring countries.
- Creating a $PM_{2.5}$ satellite database, geographic information data, and data from automated monitoring stations, totaling one set of spatially comprehensive databases covering Thailand and neighboring countries.
- Creating a prototype geospatial information service platform for $PM_{2.5}$ management and administration.

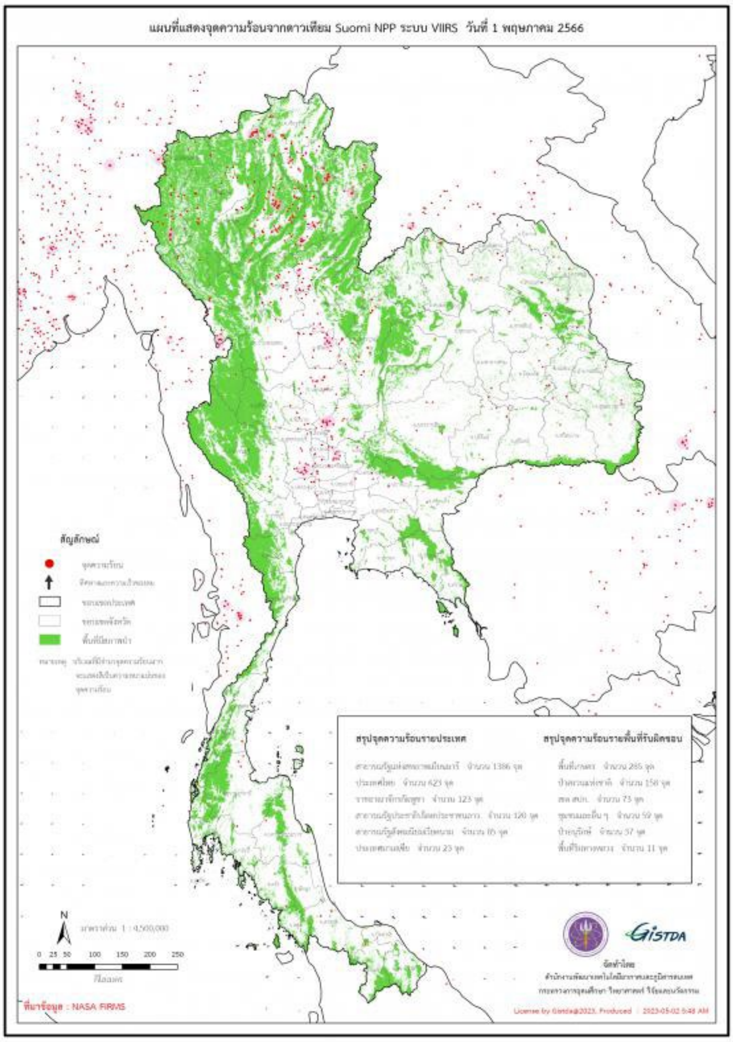

Figure 37: Daily summarized data in the form of maps by GISTDA *(GISTDA, 2023)*

There are many more websites than GISTDA that publish fire hotspot information to the public. For example, Tamfire (http://tamfire.net/), this website developed by Chulalongkorn University, and the Active Fire Hotspot Database from Satellite Images by the Royal Forest Department of Thailand (https://wildfire.forest.go.th/firemap/index.html). Other examples include the FIRMS website (Fire Information and Resource Management System; https://firms.modaps.eosdis.nasa.gov/map/#d:24hrs;@104.1,15.9,6z), Firecast (https://firecast.conservation.org/data-maps/live-view) for sharing the global hotspot map worldwide, and Wildfire Aware (https://livingatlas.arcgis.com/wildfireaware/#) for sharing the global hotspot map in the U.S., as shown in Figure 38 - Figure 42.

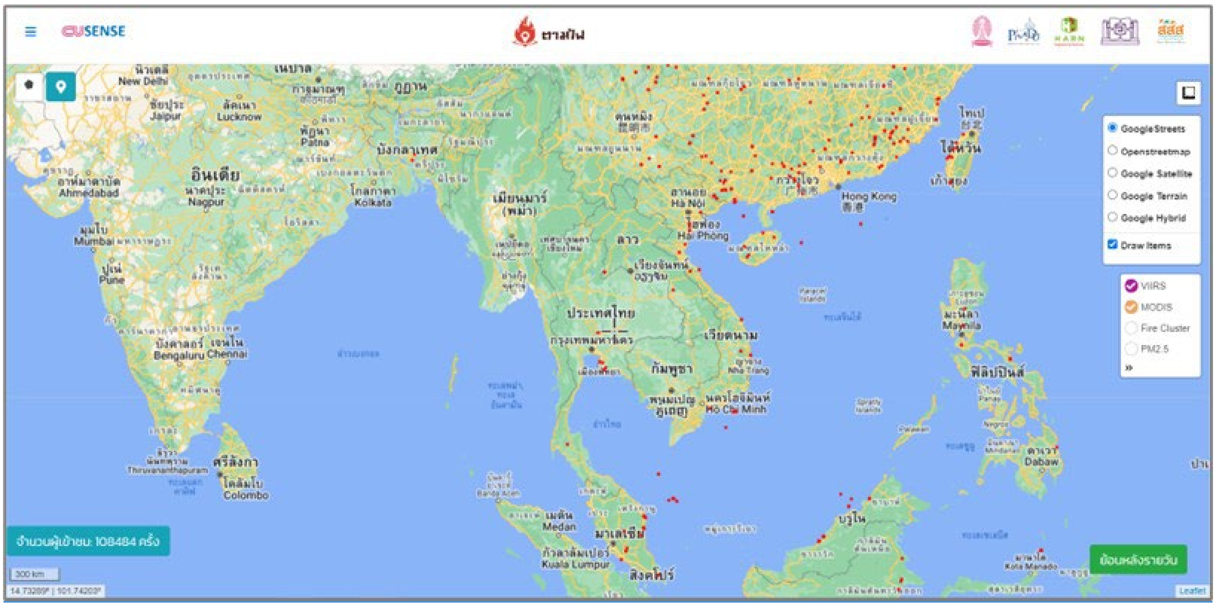

Figure 38: Tamfire (http://tamfire.net/)

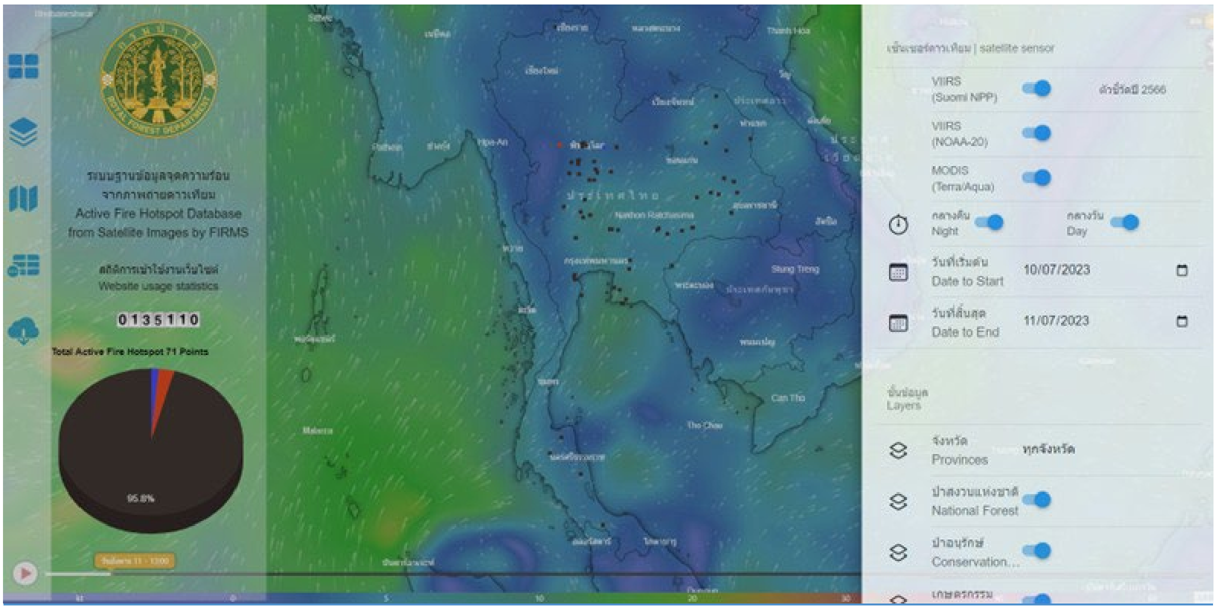

Figure 39: RFD Active Fire Hotspot (https://wildfire.forest.go.th/firemap/index.html)

Figure 40: FIRMS (https://firms.modaps.eosdis.nasa.gov/map/#d:24hrs;@104.1,15.9,6z)

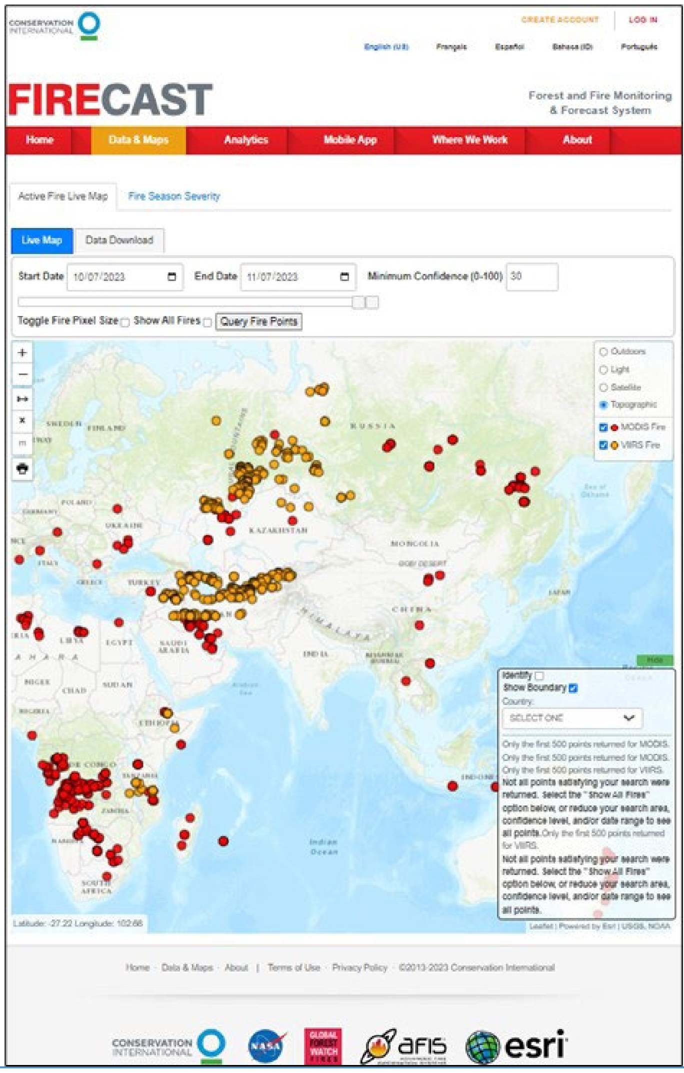

Figure 41: Firecast (https://firecast.conservation.org/data-maps/live-view)

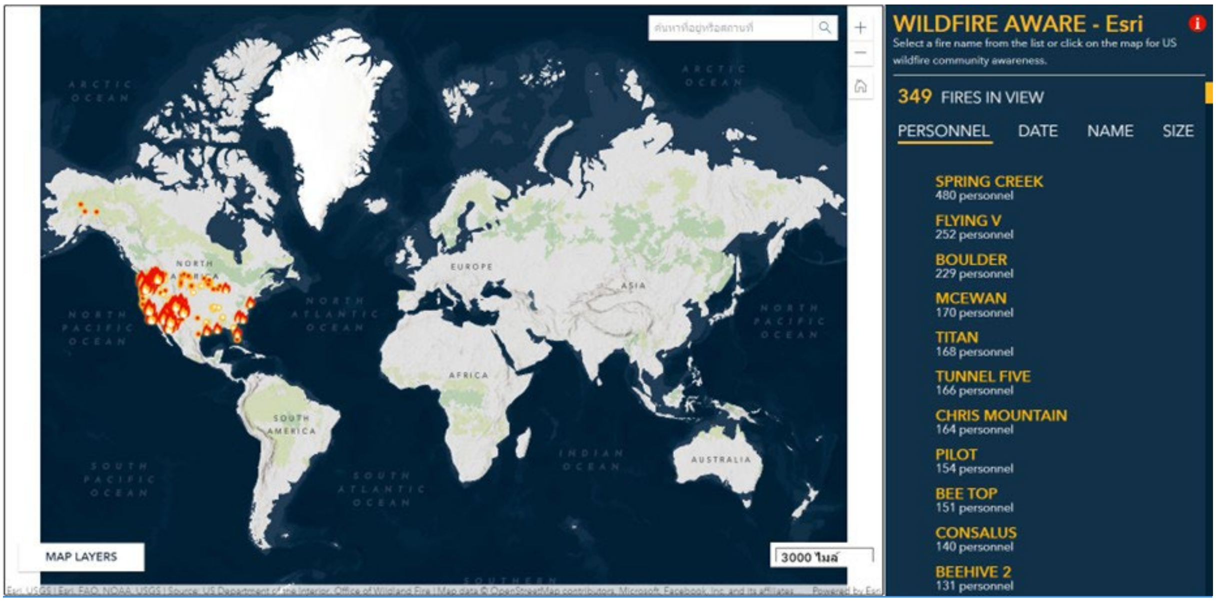

Figure 42: Wildfire aware (https://livingatlas.arcgis.com/wildfireaware/#)

From the National Agenda for action plans "Solving the dust pollution problem" in Thailand for the period 2019-2024, Thailand has set the goal to reduce the number of hotspots as one of the indicators in the action plan (PCD, 2019). Additionally, in the Ad Hoc Plan on Solving the Dust Pollution Problem in Bangkok 2023, the plan for open burning control measures will be implemented when the $PM_{2.5}$ concentration reaches level 2 ($PM_{2.5}$ concentration between 37.6-50 $\mu g/m^3$). Hotspots will be monitored and tracked in the Bangkok Metropolitan Region through the GISTDA website to address open burning issues and coordinate efforts with local administration to solve the problem (BMA, 2022).

Advantages of satellite detection are as follows:

- Satellite detection has benefits for the inspection of forest fires and forest fire management. It can provide information to public websites without any cost.
- Processing hotspot data takes only a few hours after receiving satellite information.
- This hotspot data is highly beneficial for agencies involved in fire control.
- Satellite data allows retrospective analysis, which is beneficial for hotspot mapping, identifying causes and trends, and assisting in addressing to prevent forest fires before or when it occurs.
- Many research have been using satellite aerosol optical depth (AOD) retrievals to estimate PM_{10} and $PM_{2.5}$ (Prof. Muhammad Bilal , 2021).
- It can be used to evaluate the damaged area caused by forest fires before, during, and after the incidents (NASA, 2021).

Disadvantages of Satellite detection are as follows (Channarong J. et al., 2022):

- Satellite has a very large scale of spatial detection per pixel, which leads to limited accuracy, making it unable to determine the size and quantity of fire clusters in each pixel.
- Insufficient lighting may hinder the detection of satellites.
- Satellites cannot analyze land use or land cover, which would provide insights into motivations for burning and preventive measures against recurring fires.

- Citizens who have knowledge of satellite detection systems may evade agricultural burn during the time that the satellite passes over that area, e.g., between 08:00-09:00 and 15:00-24:00.
- Satellites cannot detect hotspots obstructed by clouds, smoke, or dense undergrowth.
- Government agencies often use solely hotspot detection as a quantitative indicator, but they lack in-depth analysis of burned areas and land cover, which hinders understanding of the true causes of forest fires in terms of "quality" rather than just "quantity."

9. Remote sensing for vehicle exhaust emissions

The Remote Sensing Device (RSD) is a technology used to inspect and monitor exhaust emissions from the transportation sector as vehicles are driven past the remote sensing device on streets and highways. The emissions are measured spectroscopically by casting a narrow infrared (IR) and ultraviolet (UV) beam of light across the road and through the trailing exhaust of passing motor vehicles. A mirror then reflects the IR/UV light back to a series of detectors that measure the amount of transmitted light at characteristic wavelengths absorbed by the pollutants of interest. Remote sensing can measure pollutants such as hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen monoxide and dioxide (NO and NO_2 separately, combined as NOx), ammonia (NH_3), and particulate matter as a proxy for opacity. By taking the ratios of the various pollutants to CO_2 and applying stoichiometric rules and other conversion factors, the emission values can be estimated in units such as grams per kilogram of fuel burned (g/kg fuel burned), which can then be converted to traveled distance emissions (g/km) with appropriate assumptions (Borken-Kleefeld et al., 2018; Huang et al., 2018; OPUS, 2023). The processing of remote sensing inspection is presented in Figure 43 and Figure 44.

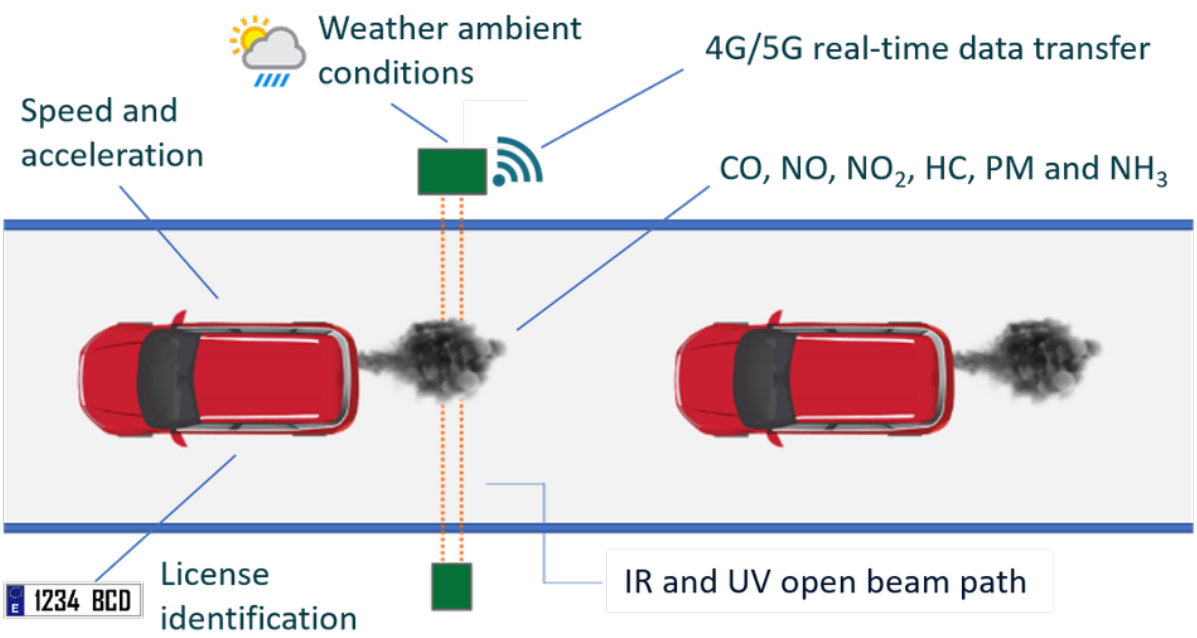

Figure 43: Remote sensing for vehicle inspection *(OPUS, 2023)*.

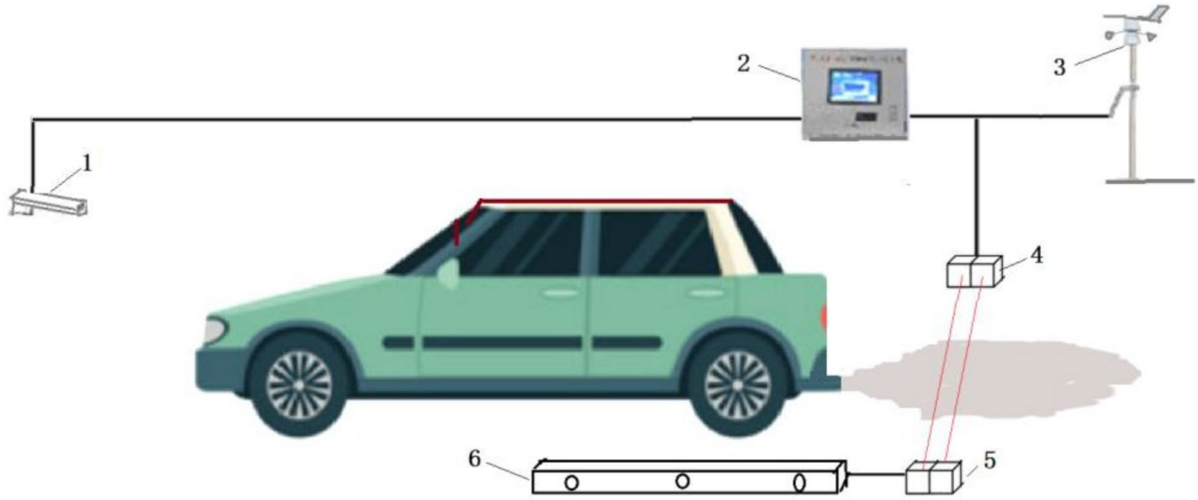

Figure 44: Schematic of vehicle emission remote sensing system. **1.** License plate camera; **2.** main control computer; **3.** weather station; **4.** light source and detector; **5.** reflector; **6.** Speedometer *(Ren X. et al., 2022)*

Vehicle exhaust emission measurements by remote sensing have been performed in several countries in Europe since 1991, such as Sweden, Switzerland, the United Kingdom, and Spain (Borken-Kleefeld et al., 2018). Early studies (1997 and earlier) mainly relied on CO measurement and were aimed at evaluating the effectiveness and accuracy of remote sensing. For post-1997 studies, the remote sensing device was developed to detect other pollutants such as HC, NO, and PM (Huang et al., 2018). Pollution from the transportation sector can be significantly reduced if a remote sensing device is applied to identify dirty vehicles, and certain measures are taken, such as automobile maintenance, tolls, and taxes.

Remote sensing can measure the instantaneous emissions of a large number of vehicles under real driving conditions at a relatively low cost, making it an ideal tool for identifying both high-emitting and clean vehicles. The former application is aimed at detecting dirty vehicles for inspection and maintenance (I/M) programs, while the latter one is to exempt clean vehicles from mandatory periodic inspections, reducing inconvenience and cost for both vehicle owners and governmental regulators (Huang et al., 2018). The case study in Illinois has compared the cost of each testing method. The cost of I/M testing was estimated at 23 million USD. However, a remote sensor is priced at 50,000 USD, and the cost of remote sensing operation is estimated to be 0.50 USD per test plus 1.00 USD for a certificate for each passing vehicle. Hence, the overall cost of remote sensing testing equals 3 million USD, making it the most economical emission testing method on a cost-per-vehicle basis (Stedman and Bishop, 1990).

For example, the successful case study in Hong Kong when Hong Kong implemented a remote sensing screening program to identify high-emission light-duty vehicles on the road, as shown in Figure 45. Vehicles detected with high emissions must be repaired and tested at an authorized Emissions Testing Centre within 12 working days. After that, it was required to pass a short transient chassis dynamometer emission test, the Hong Kong Transient Emission Test (HKTET), to remain registered and roadworthy. The Hong Kong Environmental Protection Department (HKEPD) remote sensing enforcement program reported that roadside concentrations of PM_{10} and $PM_{2.5}$ were reduced by 16% and 13%, respectively, during 2015–2016 (Huang et al., 2018; Borken-Kleefeld et al., 2018).

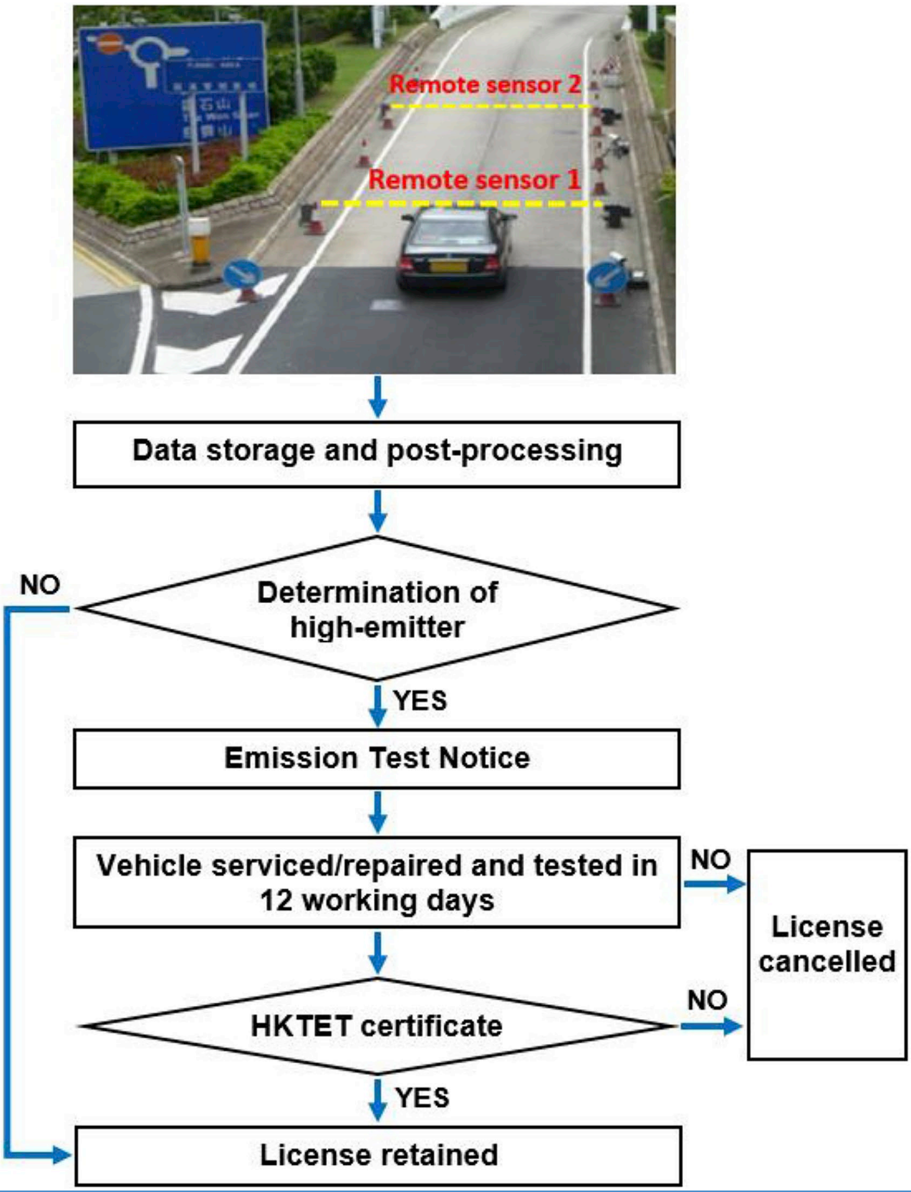

Figure 45: The process of the HKEPD remote sensing enforcement program *(Huang et al., 2018)*.

For Thailand, with the Ad Hoc Plan on Solving the Dust Pollution Problem in Bangkok 2023 (announced on 25 October 2022), there was a plan to address the $PM_{2.5}$ problem in Bangkok by using CCTV to inspect and record the license plate of vehicles that have high exhaust emissions (BMA, 2022). However, the smoke meter (filter type) and opacity meter are still used as standard devices to measure vehicle exhaust emissions. Vehicles will be banned from use, and the owner will be charged 5,000 Thai Baht if it emits smoke more than 30% measured by the opacity meter and 40% measured by the smoke meter (filter type) (ONEP, 2022).

Advantages of vehicle remote sensing are as follows:

- The major advantage of remote sensing is its ability to rapidly measure a large number of vehicles under real-world driving conditions at a relatively low cost (reduced by 30% of its current cost) (Stedman and Bishop, 1990). Remote Sensing (RS) can measure the emissions of a vehicle in less than 1 second, and a time interval of 4 seconds between two vehicles will not have significant interference on the measurements, which can be used to monitor long-term emission trends of on-road fleets (Huang et al., 2018; Liu S. et al., 2023).

- RS is currently one of the most economical technologies for measuring real-world vehicle emissions. The cost of remote sensing is minimal, less than 0.5 USD per test (Huang et al., 2018; Liu S. et al., 2023).
- RS has high accuracy and correlates with other similar technologies, such as PEMS, by up to 95% (OPUS, 2023). In addition, over the last three decades, several RS-based studies have been conducted (Liu S. et al., 2023).
- Thousands of statistically representative vehicle samples can be collected through RS technology and be further matched according to the brands or vehicle types to facilitate a more accurate analysis of fleet emissions (Liu S. et al., 2023).
- RS technology can be used for the recognition of cleaning vehicles and high-emission vehicles based on real-time emission data, thus increasing the on-load law enforcement and supervision efficiency (Liu S. et al., 2023).
- Vehicle fleet information, which is acquired by RS technology, can be used directly to evaluate the pollutant emission rate of vehicle fleets in specific regions, validating any proposed traffic emission model (Liu S. et al., 2023).

Disadvantages of vehicle remote sensing are as follows:

- Remote sensing only measures a vehicle's emissions in less than 1 second under one engine condition. When it comes to an individual vehicle, it may be insufficient to accurately characterize a vehicle's emission performance with just a single instantaneous pass-by measurement. Even normally functioning engines may have emission spikes. For the purposes of high-emitter or clean-vehicle screening, extra information and filters are required to increase the confidence in the assessment of an individual vehicle's emissions and thus to decrease false detections (Huang et al., 2018).
- Uncertainties of remote sensing are relatively large compared with laboratory emission testing and PEMS (Huang et al., 2018).
- Remote sensing measurements can only be taken in traffic with a single lane (possible in dual-lane traffic, but not preferred) and in dry weather with a clean environment (Huang et al., 2018).
- It is easy to cause misjudgment because the high-emitting vehicles may pass emission tests due to low emissions when driving at low load or low speed. On the other hand, some low-emission vehicles may be misjudged as high-emitters due to their higher emissions under high loads (Hao et al., 2021).
- The application of Remote Sensing Devices (RSDs) has achieved good results for measurements of CO, HC, and NOx concentration emissions from gasoline vehicles but has a high false rate in detecting the tailpipe emission concentrations for diesel vehicles (Hao et al., 2021).
- Since vehicle exhaust is diluted by the air after being discharged, the concentration of the exhaust plume is affected by many factors such as ambient wind speed, wind direction, and airflow disturbance. Therefore, the measured concentrations of various emission components in the exhaust plume are not the true exhaust emission concentrations (Ren X. et al., 2022).

10. Weather Research and Forecasting /Chemistry Model (WRF-Chem model)

The Weather Research and Forecasting (WRF) model is a versatile numerical weather prediction and atmospheric simulation system used for both research and operational purposes. It is a collaborative effort involving multiple agencies and organizations, including the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the Department of Defense, and more, with contributions from university scientists.

WRF features flexible and efficient code, making it suitable for various computing environments, from supercomputers to laptops. It can be configured for both research and operational applications, offering a range of physics and dynamics options influenced by the scientific community. WRF includes the WRF-Var variational data assimilation system for optimizing initial conditions and the WRF-Chem model for air chemistry modeling.

This community-supported model is used globally for research, operations, and education, covering a wide range of applications, including real-time numerical weather prediction, data assimilation, parameterized physics research, regional climate studies, air quality modeling, and more. Currently, it boasts over 6,000 registered users and is in operational and research use worldwide (NCAR, 2023; Skamarock et al., 2008).

The possible applications of the current modeling system are as follows (Peckham et al. , 2012):

- Prediction and simulation of weather, or regional and local climate.
- Coupled weather prediction/dispersion model to simulate the release and transport of constituents.
- Coupled weather/dispersion/air quality model with full interaction of chemical species with the prediction of O_3 and UV radiation as well as particulate matter (PM).
- Study of processes that are important for global climate change issues. These include but are not restricted to aerosol direct and indirect forcing.

From the National Agenda for action plans "Solving the dust pollution problem" in Thailand for the period 2019-2024, the Pollution Control Department (PCD) has developed an air pollution forecasting system to forecast air quality in selected areas, including the Bangkok Metropolitan Region and Northern Thailand (PCD, 2019). Additionally, in the Ad Hoc Plan for Solving the Dust Pollution Problem in Bangkok 2023 (announced on October 25, 2022), there is a long-term plan to support education and research using specialized atmospheric modeling for dust and pollution (BMA, 2022).

In 2021, PCD collaborated with the National Electronics and Computer Technology Center (NECTEC) to use High-Performance Computing (HPC) for forecasting fine particulate matter ($PM_{2.5}$) concentrations three days in advance, covering the Bangkok Metropolitan Region and 17 northern provinces. The benefit of using HPC is a significant reduction in processing time, approximately 10 times faster compared to a general-purpose computer. Additionally, the results obtained are highly detailed and provide more accurate interpretations of air quality (PCD, 2022; PCD, 2021; NSTDA, 2021).

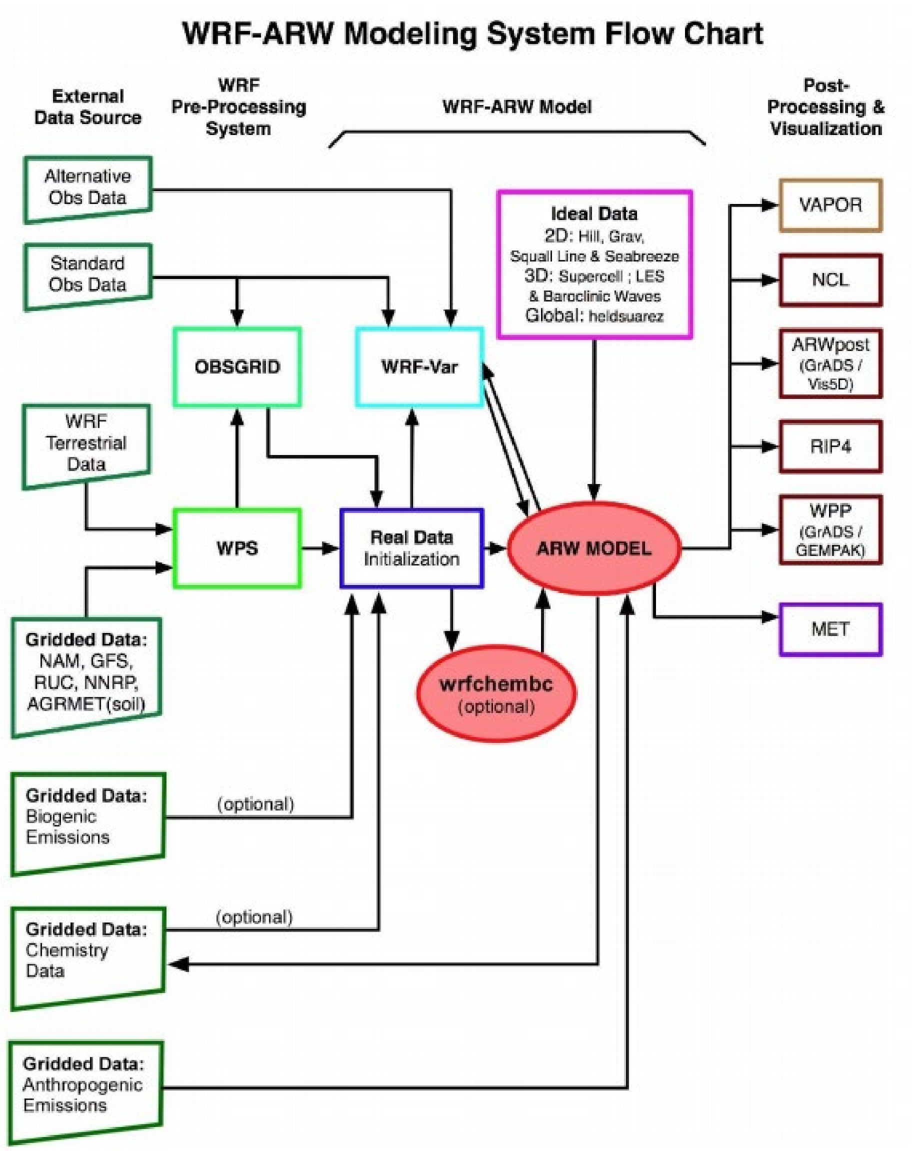

Figure 46: The WRF-Chem modeling system overview *(Peckham et al. , 2012)*

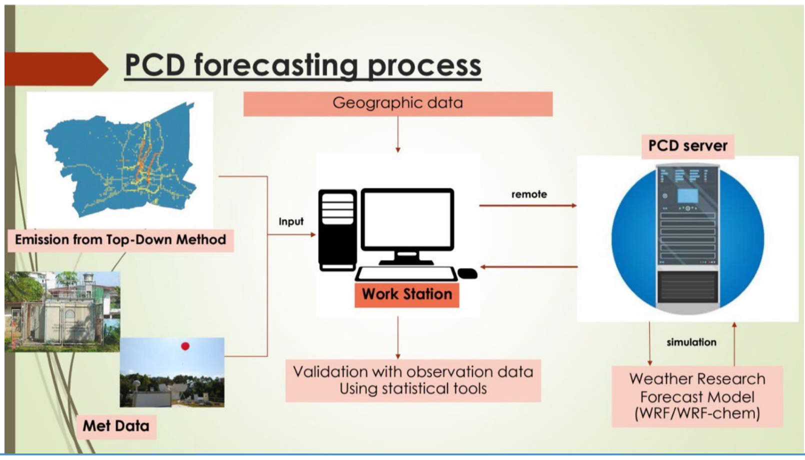

Figure 47: WRF-Chem model forecasting process by the Pollution Control Department of Thailand

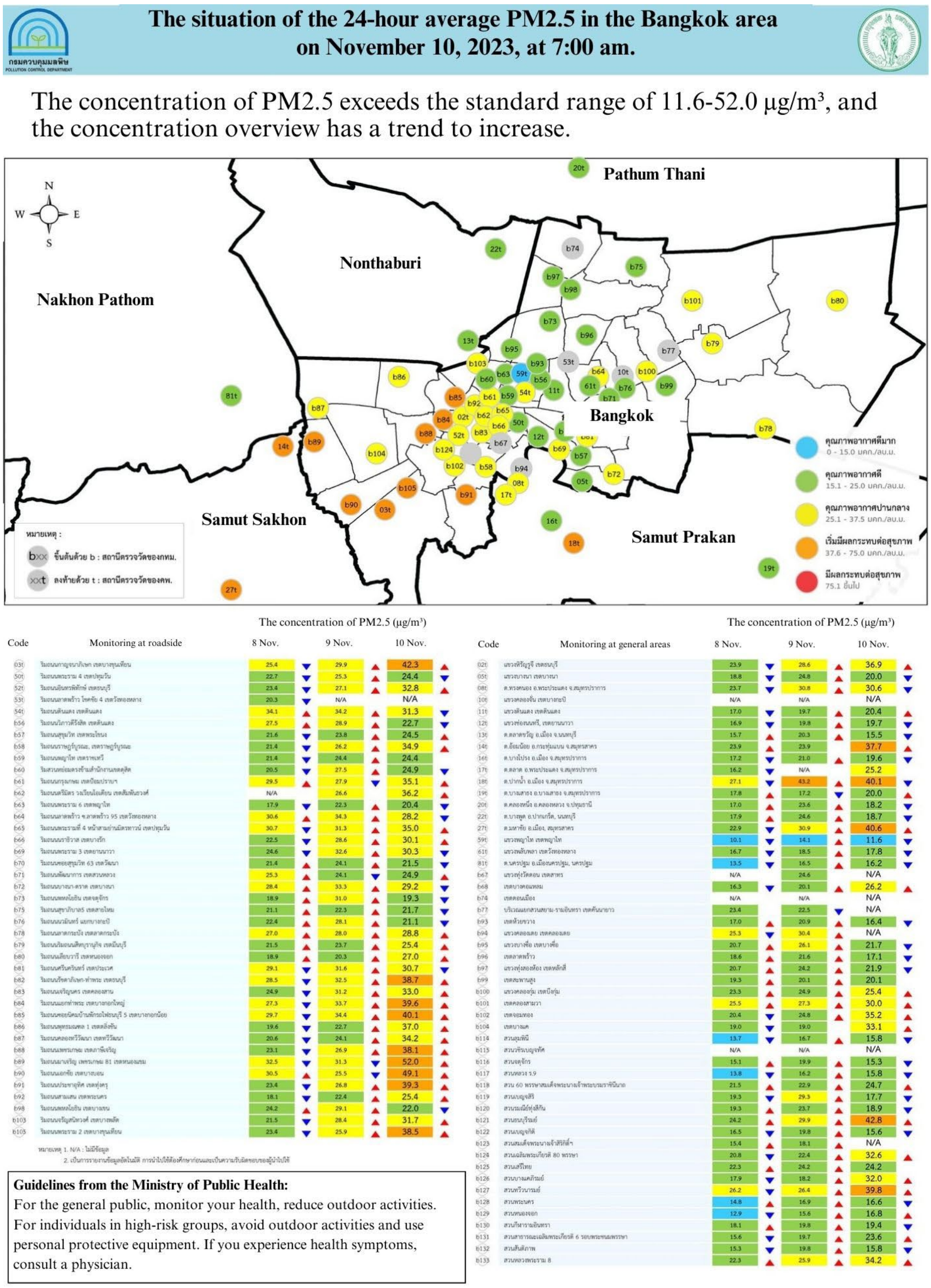

Figure 48: Example of air quality simulation generated by WRF-Chem *(PCD, 2022)*

Advantages of the WRF-Chem model are as follows:

- PCD can forecast fine particulate matter ($PM_{2.5}$) concentrations for three days in advance (NSTDA, 2021).
- The model is one of the tools used to suggest optimal solutions for short- and long-term haze-free strategic planning (PCD, 2022).
- The model assists in notifying the public, allowing them to plan outdoor activities properly (PCD, 2022).

Disadvantages of the WRF-Chem model are as follows:

- Forecasting air pollution requires a high-performance computing system (NSTDA, 2021).
- The model requires updated input data, such as emission inventory, for accuracy in evaluation.

Table 11: Summary and Comparison of the cost of each Technology

Technology		Price ranges for each technology (USD)	Operational cost (USD)
Low-cost sensor (Clements et al., 2022)		100 to 5,000	-
Diesel Particulate Filter (DPF) (DPF Clean, 2023)		Cost of DPF filter replacement can range from 2,000 to 4,000	Cost of DPF cleaning is around 179 to 500
Low Emission Zone (Watkiss et al. , 2003) Noted: it is the cost of LEZ project in London		Setup cost estimate at 3,440,878 USD	Annual running cost is 4,913,700 USD
Electric vehicle	EV (EVAT, 2023)	9,148 to 227,958 USD	-
	E-Bus (KMITL, 2016)	302,332 USD	Maintenance cost in the first 5 years is estimated at 18.33 USD/unit/day, and in the subsequent 6-10 years, it is estimated at 35.75 USD/unit/day
CEMs (Chien et al., 2003)		Installation cost is 366,000 USD.	The yearly operating cost is 27,000 USD
Cleaner stoves (Filmanovic M.E. , 2023).		2- 100 USD	-
Burn check Application for open burning		98,398 USD	-
Satellite detection for open burning			-
Remote Sensing for vehicles (Stedman and Bishop, 1990)		The remote sensor is priced at 50,000 USD	Operation cost is estimated at 0.50 USD/test
WRF-Chem model		NA	-

3. ANALYSIS OF THE TECHNOLOGIES AND GAPS FOR AIR POLLUTION CONTROL IN BANGKOK CITY

Based on the current air quality situation in Bangkok and the results from the emission inventory, this study focuses on technologies to reduce fine particulate matter ($PM_{2.5}$). All "Technical Tools in Air Quality Management" are assessed to identify readiness and gaps for each technology using the technology readiness matrix (Table 19). The information used for the assessment is based on innovativeness, affordability, availability, and $PM_{2.5}$ reduction potential. The score is determined through assessment by AIT and interviews with policymakers working on air quality management in Thailand.

Table 12 provides an explanation of the innovativeness of the technology used in this assessment. It indicates that "High" innovation refers to technologies that have been used after 2019, "Medium" innovation refers to technologies that have been used during 2000–2019, while "Low" innovation refers to technologies that have been used before 2000.

Table 12: Description of the innovativeness parameter to assess the readiness of technology

Innovativeness	Meaning
High	Technologies have been used after 2019, or the implementation adopts technologies for use in Thailand after the announcement of the National Agenda for action plans "Solving the dust pollution problem" in Thailand for the period 2019-2024.
Medium	Technologies have been used since 2000, and the implementation adopts technologies for use in Thailand before the announcement of the National Agenda for action plans "Solving the dust pollution problem" in Thailand for the period 2019-2024.
Low	Technologies have been used before 2000's

Table 13 provides an explanation of the affordability of the technology used in this assessment. It indicates that "High" affordability refers to technologies that can be purchased by everyone, "Medium" affordability refers to technologies that can be purchased with support from the government, while "Low" affordability refers to technologies that can be purchased by only the private sector (e.g., bus fleet owner) and government.

Table 13: Description of the affordability parameter to assess the readiness of technology

Affordability	Meaning
High	Users can access and purchase technologies.
Medium	Users need support from the government to purchase technologies.
Low	Users cannot purchase technologies, but the private sector and government can access technologies.

Table 14 provides an explanation of the availability of the technology used in this assessment. It indicates that "High" availability refers to technologies that people are familiar with in Thailand, "Medium" availability refers to technologies that some people are using in Thailand, while "Low" availability refers to technologies that are currently not being used in Thailand.

Table 14: Description of the availability parameter to assess the readiness of technology

Availability	Meaning
High	The number of devices within Thailand is sufficient to solve the $PM_{2.5}$ pollution problem. Moreover, there are several companies in Thailand capable of developing and producing the devices on their own.
Medium	There are tools being used in Thailand, but their quantity is still insufficient to solve the $PM_{2.5}$ pollution problem. People in the country are beginning to gain knowledge on using technology, but it is not enough to enable the development and production of devices for use in Thailand.
Low	Technology is still not available to be used in Thailand, but it is available and used in other countries. Thailand still relies on tools and knowledge from collaboration with other countries for data analysis, tool development, and efforts to adapt technology for use in the country.

Table 15 provides an explanation of the score used to assess technologies to reduce air pollution in Bangkok. In this study, the "Importance of the problem" and "Efficiency of the technology" are used in the analysis.

Table 15: Assessment of $PM_{2.5}$ Reduction Potential Based on Scientific Data (Matrix 3×3)

Technology Assessment Scores			
Importance of problem	Efficiency of the technology		
	Low (1)	Medium (2)	High (3)
Low (1)	2	3	4
Medium (2)	3	4	5
High (3)	4	5	6

The criteria for assessing $PM_{2.5}$ reduction potential in each technology are as follows:

Description of "Importance of problem"

"Importance of problem" refers to the sector that Bangkok should take action on because it is the main sector that produces $PM_{2.5}$ in Bangkok, and it needs technology to solve the problem. This information is based on the Emission Inventory of $PM_{2.5}$ in Bangkok for the base year of 2019 (Winijkut et al., 2020) as follows (as discussed previously in Figure 8):

1. Transportation sector (Transportation and Road dust) emits 55% of Bangkok $PM_{2.5}$ emission.
2. Agricultural sector (Agricultural open burning) emits 20% of Bangkok $PM_{2.5}$ emission.
3. Industrial sector (Factories and Power plants) emits 12% of Bangkok $PM_{2.5}$ emission.
4. Residential sector (Street food& markets and Household) emits 12% of Bangkok $PM_{2.5}$ emission.

The description of the "Importance of Problem" is provided in Table 16. For the "Efficiency of the technology," which refers to how much $PM_{2.5}$ emission per unit (e.g., one car) can be reduced by using that technology, the meanings of High, Medium, and Low are provided in Table 17.

Table 16: Description of "Importance of the problem"

Importance of problem	Meaning
High	Technology helps to reduce and manage $PM_{2.5}$ emitted from the transportation and agricultural sectors.
Medium	Technology helps to reduce and manage $PM_{2.5}$ emitted from industrial sectors.
Low	Technology helps to reduce and manage $PM_{2.5}$ emitted from other sectors that are not included in "High" and "Medium."

Table 17: Description of "Efficiency of technology"

Efficiency of technology	Meaning
High	The technology has the efficiency to reduce $PM_{2.5}$ at the source by over 50%, and the technology is feasible to be implemented in Bangkok.
Medium	The technology has the efficiency to reduce $PM_{2.5}$ at the source by less than 50%, but the technology still has the potential to be implemented in Bangkok.
Low	The technology does not help to reduce $PM_{2.5}$ emissions, or there is no report on its effectiveness in reducing $PM_{2.5}$, or the technology is the device used for the measurement and monitoring of $PM_{2.5}$ levels and must be utilized in conjunction with other social measures to reduce $PM_{2.5}$. In addition, the technology still has gaps in policy, and it is difficult to be implemented in Bangkok.

The summary of the score refers to the possibility of emission reduction when using those technologies in Bangkok, and the classification of the scores in this study is provided in Table 18.

Table 18: Description of technology assessment score

Efficiency of device	Meaning
5-6	The technology has a high potential to reduce $PM_{2.5}$ in Bangkok
3-4	The technology has medium potential to reduce $PM_{2.5}$ in Bangkok
1-2	The technology has low potential to reduce $PM_{2.5}$ in Bangkok

Table 19: Assessment of Technology Readiness Matrix

Technologies	Rank						Practical: Comments on the potential for success in implementation in Bangkok (Report and interviews and personal communication) *
	Innovativeness (Operation year)	Affordability	Availability	$PM_{2.5}$ reduction potential			
				Importance of problem	Efficiency of technology	Score	
Low-cost sensor	2012 (Dye T., 2023)	High	High	Low (1)	M (1)	2	Should be certified by USEPA, and follow the standard method to calculate Air Quality Index.
Diesel Particulate Filter (DPF)	1981 (Majewski, 2020)	Medium	Medium	High (3)	S: up to 90% (3)	6	Need financial support from the government to implement. These should be options for fleet owners, not individuals.
Low Emission Zone	1990 (Jens M et al., 2019)	Medium	Medium	High (3)	S: depends on the location (1)	4	Difficult to implement since it is related to different organizations in Thailand.
Electric vehicle	2010 (Matulka R., 2014)	Medium	Medium	High (3)	S: 100% (3)	6	Need more electric boats and vehicles to make the price more competitive.
CEMs	2001 (Leungsakul S., 2021)	Low	Medium	Medium (2)	M (1)	3	Should include a “Smart Boiler” with IoT and a cleaner crematorium and waste incinerator.

Table 19: *(Continued)*

Technologies	Rank						Practical: Comments on the potential for success in implementation in Bangkok (Report and interviews and personal communication) *
	Innovativeness (Operation year)	Affordability	Availability	$PM_{2.5}$ reduction potential			
				Importance of problem	Efficiency of technology	Score	
Cleaner cooking	1973 (PTT, 2023)	High	High	Low (1)	S: 95% (3)	4	Difficult to implement since it is related to the income of people (street food).
Burn check Application for open burning	2021 (Haze Free Thailand, 2021)	High	Medium	High (3)	S: depends on the location (2)	5	Should include technology to make products and fuels from agricultural wastes.
Satellite detection for open burning	1999 (Channarong J. et al., 2022)	Low	Low	High (3)	S: depends on the location (2)	5	Should explore new satellites, such as the GEMS satellite to get better data.
Remote Sensing for vehicles	2000 (Huang et al., 2018)	Low	Low	High (3)	M (1)	4	Should be used in Thailand, but the cost is high for the government.
WRF-Chem model	1990 (NCAR, 2023)	Low	Medium	Low (1)	M (1)	2	Currently used in Thailand (Bangkok area included)

Noted: S: Percent of PM2.5 reduce at Source, M: monitoring device. (Panyametheekul S. et al., 2022; Chavanaves et al., 2021); *interviewed Thai Pollution Control Department staffs (Environmentalist, Professional level) and personal communication with members of the Thai Environmental Engineering Association.

4. CONCLUSION AND RECOMMENDATION

Five air pollutants have been monitored in the ambient air in Thailand: PM, CO, NOx, Ozone, and SOx. However, only $PM_{2.5}$ and Ozone are still problems in different areas. The current condition of air quality in Bangkok shows improvement in terms of annual $PM_{2.5}$ concentration, while 24-hour $PM_{2.5}$ concentration is still higher than the NAAQS in different parts of the country, especially during the dry season. Moreover, the concentration of Ozone, which is a secondary pollutant, is still high in different areas in Thailand, indicating that proper management should be implemented to control precursors and ozone emissions in the near future. Emission inventory of $PM_{2.5}$ in Bangkok (based on 2019 data) shows three major emission sources, which are transportation (55%), open burning (20%), and industry (11%), while the rest accounts for only 14% of total $PM_{2.5}$ emitted in the Bangkok area.

Based on the air quality monitoring and emission inventory information in Bangkok, this report focuses on the technologies to reduce only $PM_{2.5}$ emissions in Bangkok. Ten technologies and approaches have been reviewed and ranked by the impacts to reduce $PM_{2.5}$ emissions in Bangkok as follows:

- High $PM_{2.5}$ Reduction Potential: Diesel Particulate Filter, Electric Vehicle, Burn Check application, and Satellite detection of burning hotspots.
- Medium $PM_{2.5}$ Reduction Potential: Low Emission Zone, Remote sensing for vehicles, cleaner cooking and street food and CEMs.
- Low $PM_{2.5}$ Reduction Potential: Low-cost sensor for ambient air quality monitoring and WRF-Chem model.

Interview and discussion with different individuals working related to air quality management in Thailand were also conducted to get suggestions and gaps in the technology assessment and technology implementation in Bangkok. The suggestions include the difficulties in implementing Low Emission Zone and Clean cooking and street food since it involves different organizations that need to work closely together and may affect the income of the people (in the case of cleaner cooking for street food). The recommendations also extend to the fact that there are needs for "technology to convert agricultural wastes to other products, ex. biofuel, pellets" and "technology on smart boiler with IoT and improved incinerator" in Bangkok. In general, all nine technologies and approaches are practical for a small-scale implementation, but there is still a shortage of mechanism to expand it to a larger area (knowledge transfer and funding/tax supports).

However, this report did not evaluate technologies that help to control $PM_{2.5}$ emissions from the industrial sector, such as Flue Gas Desulfurization (FDGs), Electrostatic precipitators (ESPs), Filters and dust collectors (baghouses), Wet scrubbers, and Low-NOx burners, since these technologies have been used in the industrial sector in Thailand to comply with Thailand's emission standard (not specifically in the Bangkok area). The technology adoption depends on the decision of the factory owners and depends on the suitability of the type of factory, ensuring that pollutant emissions from the sources comply with the emission standards. In addition, Thailand has a policy to control the location of the industry. The regulations under the Ministry's 2nd version of the Factory Act of 1992 prohibit the factories, considered air pollution sources, from being established in proximity to public facilities such as schools, temples, hospitals, historical sites, and government agency workplaces within a distance of either 50 or 100 meters, depending on the case. Additionally, the new industrial factories in Thailand must do an environmental impact assessment (EIA) before establishing the factory (Thuamkred P. et al., 2020). Hence, in the Bangkok area, there is a relatively high level of readiness and feasibility in terms of measures and technologies for controlling $PM_{2.5}$ from the industrial sector.

Furthermore, measures and technologies that help to control dust from construction activities are not included in this study. However, the Pollution Control Department has provided comprehensive guidelines with primary requirements (PCD, 2003) in Thailand. For instance:

1. Manage construction material within an enclosed area with solid barriers on the top and three sides to prevent the dispersion of dust.
2. Tarpaulins covered trucks during transportation to prevent dust dispersion.
3. Clean and remove any soil or sand residues from vehicle wheels before they leave the project area, and provide appropriate cleaning facilities within the project area.
4. Construct barriers around the construction area, at least 2 meters high from the ground, to prevent the dispersion of dust, soil, or sand beyond the construction site, especially in areas near residential communities.
5. Temporarily treat road surfaces with semi-permanent materials such as Asphalt or apply chemical substances like vinyl or latex to prevent dust dispersion in areas awaiting installation or relocation of public utility systems.

REFERENCES

Asian Development Bank (ADB). (2013). *Improving Air Quality Monitoring in Asia*. Asian Development Bank. https://cleanairasia.org/sites/default/files/2021-05/19.%20Improving%20Air%20Quality%20Monitoring%20in%20Asia%20-%20A%20Good%20Practice%20Guidance.pdf

Air Quality Life Index (AQLI). (2022). *Thailand Fact Sheet*. Air Quality Life Index, https://aqli.epic.uchicago.edu/wp-content/uploads/2022/03/Thailand-FS.pdf

Bhattacharya, S. C., & Salam, P. A. (2002). Low greenhouse gas biomass options for cooking in the developing countries. Biomass and Bioenergy, 22(4), 305-317. https://doi.org/10.1016/S0961-9534(02)00008-9

Bangkok Metropolitan Administration (BMA). (2013). *Executive Summary 20-year Development Plan for Bangkok Metropolis*. Strategy and Evaluation Department Bangkok Metropolitan Administration and Faculty of Political Sciences, Chulalongkorn University. https://webportal.bangkok.go.th/public/user_files_editor/130/BMA-developmentplan/P20ys(2556-2575)sumEN.pdf

Bangkok Metropolitan Administration (BMA). (2022). *Ad Hoc Plan on Solving Dust Pollution Problem in Bangkok 2023*. Air Quality and Noise Management Division under the Department of Environment Bangkok Metropolitan Administration. https://circular.bangkok.go.th/doc/20221028/7901.pdf

Borken-Kleefeld, J., & Dallmann, T. (2018). Remote sensing of motor vehicle exhaust emissions. *The International Council on Clean Transportation*. https://theicct.org/sites/default/files/publications/Remote-sensing-emissions_ICCT-White-Paper_01022018_vF_rev.pdf

Carbase. (2023). *Diesel Particulate Filters: Everything You Need To Know*. https://www.carbase.co.uk/news-and-features/car-maintenance/diesel-particulate-filters/

Cleancooking Alliance (CCA). (2023). *CCA's 2022 Annual Report*. https://cleancooking.org/the-value-of-clean-cooking/

Climate Change Data Center (CCDC). (2023). *The guideline for installation, use, and maintenance of Dustboy.* Climate change data center of Chiang mai university. https://www.cmuccdc.org/guide

Channarong, J.(2022). *Knowledge about Forest Fires and Open Burning*. Center for Clean Air Solutions (CCAS). http://www.ccas.or.th/knowledge

Chien, T. W., Chu, H., Hsu, W. C., Tseng, T. K., Hsu, C. H., & Chen, K. Y. (2003). A feasibility study on the predictive emission monitoring system applied to the Hsinta power plant of Taiwan Power Company. *Journal of the Air & Waste Management Association*, *53*(8), 1022-1028. https://doi.org/10.1080/10473289.2003.10466241

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

Clements, A., Duvall, R., Green, D., & Dye, T. (2022). The enhanced air sensor guidebook. *US Environmental Protection Agency: Washington, DC, USA*. https://www.epa.gov/system/files/documents/2023-06/508%20Compliant%20-%20AirSensorGuidebook_T%26RWebinar.pdf

CUSense. (2023). *Sensor for All*. Sensor for All Chula engineering. https://sensorforall.eng.chula.ac.th/

Dieselnet. (2023). *EU: Low Emission Zones (LEZ)*. https://dieselnet.com/standards/eu/lez.php#req

Department of Industrial Works of Thailand (DIW). (2006). Announcement of the Ministry of Industry Regarding the Specification of Emission Standards for Airborne Pollutants from Factories 2006. http://cems.diw.go.th/fileupload/%E0%B8%9B%E0%B8%A3%E0%B8%B0%E0%B8%81%E0%B8%B2%E0%B8%A8%E0%B8%81%E0%B8%A3%E0%B8%B0%E0%B8%97%E0%B8%A3%E0%B8%A7%E0%B8%87%E0%B8%AD%E0%B8%B8%E0%B8%95%E0%B8%AA%E0%B8%B2%E0%B8%AB%E0%B8%81%E0%B8%A3%E0%B8%A3%E0%B8%A1%20%E0%B9%80%E0%B8%A3%E0%B8%B7%E0%B9%88%E0%B8%AD%E0%B8%87%20%E0%B8%81%E0%B8%B3%E0%B8%AB%E0%B8%99%E0%B8%94%E0%B8%84%E0%B9%88%E0%B8%B2%E0%B8%9B%E0%B8%A3%E0%B8%B4%E0%B8%A1%E0%B8%B2%E0%B8%93%E0%B8%82%E0%B8%AD%E0%B8%87%E0%B8%AA%E0%B8%B2%E0%B8%A3%E0%B9%80%E0%B8%88%E0%B8%B7%E0%B8%AD%E0%B8%9B%E0%B8%99%E0%B9%83%E0%B8%99%E0%B8%AD%E0%B8%B2%E0%B8%81%E0%B8%B2%E0%B8%A8%E0%B8%97%E0%B8%B5%E0%B9%88%E0%B8%A3%E0%B8%B0%E0%B8%9A%E0%B8%B2%E0%B8%A2%E0%B8%AD%E0%B8%AD%E0%B8%81%E0%B8%88%E0%B8%B2%E0%B8%81%E0%B9%82%E0%B8%A3%E0%B8%87%E0%B8%87%E0%B8%B2%E0%B8%99%20%E0%B8%9E.%E0%B8%A8.%202549.pdf

Department of Land Transport (DLT). (2021). *Statistics*. https://web.dlt.go.th/statistics/

Doungthai, T. (2021). Innovative Management Utilizing Applications As Communication Tools For Smog and Wildfire Prevention and Solution in Northern Thailand. Journal of Communication Arts Review, Vol. 26, No. 1. https://so06.tci-thaijo.org/index.php/jca/article/view/253701

DPF Clean. (2023). *How Much Does a Diesel Particulate Filter Replacement Cost?* Retrieved from DPF Clean: https://30minutedpfclean.com/diesel-particulate-filter-replacement-cost/

Dye, T. (2023). A Brief History of Air Quality Sensors. *Sutori.* https://www.sutori.com/en/story/a-brief-history-of-air-quality-sensors--jMm2LKEQZDWmXvsDMv2MP5LV

Energy Efficiency and Renewable Energy (EERE). (2023). *How Do All-Electric Cars Work?*. U.S. Department of Energy. https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work

Electric Vehicle Association of Thailand (EVAT). (2023), Summary of Battery Electric Vehicle Models in Thailand, *Electric Vehicle Association of Thailand*. https://drive.google.com/file/d/13Uv6WWAx9sVlLUH5hH5z0SOofCFu42kh/view

Elite garages. (2023). *Everything you need to know about ultra-low emission zone.* https://www.elitegarages.co.uk/2022/08/ultra-low-emission-zones-faqs

European Union (EU). (2022). *Urban Access Regulations in Europe*. https://urbanaccessregulations.eu/low-emission-zones-main/what-are-low-emission-zones

Filmanovic M.E. (2023). Not all cookstoves are the same, *Abatable. https://www.abatable.com/blog/cookstove-carbon-projects*

Geo-Informatics and Space Technology Development Agency (GISTDA). (2021). *Annual Report of the Operations of GISTDA of Thailand for the Fiscal Year 2021*. https://www.gistda.or.th/ewtadmin/ewt/gistda_web/article_attach/articlefile_20220426091916334 37.pdf

Geo-Informatics and Space Technology Development Agency (GISTDA). (2021). *Geostationary Environment Monitoring Spectrometer,* https://www.gistda.or.th/news_view.php?n_id=1258&lang=TH

Geo-Informatics and Space Technology Development Agency (GISTDA). (2023). *Daily hotspot map in Thailand*. https://www.gistda.or.th/news_view.php?n_id=6940&lang=TH

Greennews. (2021). *"FireD" Application manage forest fire-PM2.5 in Chiang Mai.* https://greennews.agency/?p=23771

Grieshop, A. P., Marshall, J. D., & Kandlikar, M. (2011). Health and climate benefits of cookstove replacement options. *Energy Policy*, *39*(12), 7530-7542. https://doi.org/10.1016/j.enpol.2011.03.024

Hao, L.,Yin, H., Wang, J., Wang, X., & Ge, Y. (2021). Potential of big data approach for remote sensing of vehicle exhaust emissions. *Scientific Reports 11, 5472 (2021). https://doi.org/10.1038/s41598-021-84890-7*

Haze Free Thailand. (2021). *Haze Free Thailand (Northern)*. Research University Network Cluster Climate Change and Disaster Management: RUN-CCDM. http://www.thai-explore.net/file_upload/submitter/file_upload//264f9df240b27ea42d170e905f09db116da4df953c1aca0b.pdf

Horizon power. (2023). *Electric Vehicles - The basics of what you need to know*. https://www.horizonpower.com.au/for-home/electric-vehicles/electric-vehicle-101/

Huang, Y., Organ, B., Zhou, J. L., Surawski, N. C., Hong, G., Chan, E.F.C., & Shing, Y. (2018). Remote sensing of on-road vehicle emissions: Mechanism, applications and a case study from Hong Kong. *Atmospheric Environmen*t (Vol. 182, pp. 58-74). https://doi.org/10.1016/j.atmosenv.2018.03.035

International Energy Agency (IEA). (2018). *World energy balances*. IEA World Energy Statistics and Balances. https://energyeducation.ca/encyclopedia/Total_final_consumption#:~:text=Total%20final%20consumption%2C%20also%20referred,and%20secondary%20fuels%20like%20gasoline.

IQAir. (2021). *2021 World Air Quality Report: Region & City PM2.5 Ranking*. IQAir. https://www.iqair.com/world-most-polluted-cities/world-air-quality-report-2021-en.pdf

IQAir. (2022). *2022 World Air Quality Report: Region & City PM2.5 Ranking*. IQAir. https://www.iqair.com/world-most-polluted-cities

Jens, M. (2019). *Low-Emission Zones are a success - but they must now move to zero-emission mobility*. Transport and Environment. https://www.transportenvironment.org/wp-content/uploads/2021/07/2019_09_Briefing_LEZ-ZEZ_final.pdf

Jessica, M. (2017). *Using Satellites to Monitor Open Burning*. Climate and Clean Air Coalition (CCAC) : https://www.ccacoalition.org/en/news/using-satellites-monitor-open-burning

Joshua, M., & Lingzhi, J. (2018). *Global Progress Toward Soot-Free Diesel Vehicles in 2018*. ICCT REPORT. https://theicct.org/sites/default/files/publications/Global_progress_soot_free_diesel_20180702.pdf

King Mongkut's Institute of Technology Ladkrabang (KMITL). (2016), Study of the guideline for providing 200 electric buses in Thailand. http://www.bmta.co.th/sites/default/files/files/draft-tor/3_thiimaakaarkhamnwnraakhaaklaangkhngthiiprueksaa.pdf

Kim, J., Jeong, U., Ahn, M. H., Kim, J. H., Park, R. J., Lee, H., ... & Choi, Y. (2020). New era of air quality monitoring from space: Geostationary Environment Monitoring Spectrometer (GEMS). Bulletin of the American Meteorological Society, 101(1), E1-E22. https://doi.org/10.1175/BAMS-D-18-0013.1

Kongklaew, C., Phoungthong, K., Prabpayak, C., Chowdhury, M.S., Khan, I., Yuangyai, N., Yuangyai, C., & Techato, K. (2021). Barriers to Electric Vehicle Adoption in Thailand. *Sustainability*, *13*, 12839. https://doi.org/10.3390/su132212839

Leungsakul, S. (2021). *Continuous Emission Monitoring System (CEMs)*. http://www.rrcap.ait.ac.th/apn/Documents/P4_AQM_CEMS.pdf

Liu, S., Zhang, X., Ma, L., He, L., Zhang, S., & Cheng, M. (2023). Data quality evaluation and calibration of on-road remote sensing systems based on exhaust plumes. *Journal of Environmental Sciences*, *123*, 317-326. https://doi.org/10.1016/j.jes.2022.06.003

Majewski, W. A. (2020). *Diesel Particulate Filters*. DieselNet Technology Guide. https://dieselnet.com/tech/dpf.php

Marks, D. (2020). *Drive less to help solve Bangkok's air pollution*. Bangkok Post. https://www.bangkokpost.com/opinion/opinion/2039775/drive-less-to-help-solve-bangkoks-air-pollution

Matulka, R. (2014). *The History of the Electric Car*. Department of Energy. https://www.energy.gov/articles/history-electric-car

Ministry of Energy . (2011). *20 years Roadmap of electricity conservation (2011-2030).* Ministry of Energy. https://webkc.dede.go.th/testmax/sites/default/files/%E0%B9%81%E0%B8%9C%E0%B8%99%E0%B8%AD%E0%B8%99%E0%B8%B8%E0%B8%A3%E0%B8%B1%E0%B8%81%E0%B8%A9%E0%B9%8C%E0%B8%9E%E0%B8%A5%E0%B8%B1%E0%B8%87%E0%-B8%87%E0%B8%B2%E0%B8%99%2020%20%E0%B8%9B%E0%B8%B5%20%282554-257

Ministry of Industry (MOI). (2022). *Notification of Ministry of Industry Re: Requirement for Installation of an Automatic Instrument or Equipment to Measure Quality of Air Emissions from Stacks*. Ministry of Industry. http://www.envimtp.com/info_pic/14.6.65.pdf

Nakayama, T., Matsumi, Y., Kawahito, K., & Watabe, Y. (2018). Development and evaluation of a palm-sized optical PM2. 5 sensor. *Aerosol Science and Technology*, *52*(1), 2-12. https://doi.org/10.1080/02786826.2017.1375078

National Aeronautics and Space Administration (NASA). (2021). *ARSET - Satellite Observations and Tools for Fire Risk, Detection, and Analysis*. NASA's Applied Remote Sensing Training Program. https://appliedsciences.nasa.gov/join-mission/training/english/arset-satellite-observations-and-tools-fire-risk-detection-and?utm_source=social&utm_medium=ext&utm_campaign=Wildfires-21

National Center for Atmospheric Research (NCAR), (2008). Weather Research & Forecasting Model (WRF). *the University Corporation for Atmospheric Research.* https://www.mmm.ucar.edu/models/wrf

National Institute of Environmental Research (NIER). (2020). Concept Note on Building the Pan-Asia Partnership for Geospatial Air Pollution information. https://philsa.gov.ph/wp-content/uploads/2022/06/1-Concept-Note_Building-the-Pan-Asia-Partnership-for-Geospatial-Air-Pollution-Information_20200622-1.pdf

National Science and Technology Development Agency (NSTDA). (2021). *PCD collaborates with NSTDA to use Supercomputer for forecasting PM2.5*, https://www.nstda.or.th/home/news_post/supercomputer/

Nikam, J., Archer, D. and Nopsert, C. (2021). Air Quality in Thailand: Understanding the regulatory context. SEI Working Paper. Stockholm Environment Institute. https://www.sei. org/publications/air-quality-thailandregulatory-context/

National News Bureau of Thailand (NNT). (2023). *Bangkok Electric Boat Service Comes Under BMA Review*. National News Bureau of Thailand. https://thainews.prd.go.th/en/news/detail/TCATG230109104443231

Office of Natural Resources and Environmental Policy and Planning (ONEP). (2022). *new standards of tailpipe exhaust emmission measurement that were announced on 16 April 2022*. Office of Natural Resources and Environmental Policy and Planning. https://www.onep.go.th/16-%E0%B9%80%E0%B8%A1%E0%B8%A9%E0%B8%B2%E0%B8%A2%E0%B8%99-2565-%E0%B8%A1%E0%B8%B5%E0%B8%9C%E0%B8%A5%E0%B9%81%E0%B8%A5%E0%B9%89%E0%B8%A7-%E0%B9%80%E0%B8%81%E0%B8%93%E0%B8%91%E0%B9%8C%E0%B9%83%E0%B8%AB/

OPUS. (2023). *The remote sensing device.* https://www.opusrse.com/technology/remote-sensing-device/

Panyametheekul, S.(2022). *Research Program on Integrated Technology for mitigating PM2.5: A case study in Bangkok Metropolitan Region (BMR)*. National Research Council of Thailand (NRCT). http://www.thai-explore.net/file_upload/submitter/file_upload//5c5f52490d3a05ed84df4b1170aaac0115a881a1e818930e.pdf

Parajuly, K., Ternald, D., & Kuehr, R. (2020). The Future of Electric Vehicles and Material Resources: A Foresight Brief. https://wedocs.unep.org/bitstream/handle/20.500.11822/34225/ElecVe.pdf?sequence=1&isAllowed=y

Pollution Control Department (PCD). (2003). *Measures guidelines to control PM from construction*. Retrieved from Pollution Control Department : https://www.pcd.go.th/publication/4689

Pollution Control Department (PCD). (2018). *Booklet on Thailand State of Pollution 2018*. Pollution Control Department, Ministry of Natural Resources and Environment. http://www.oic.go.th/FILEWEB/CABINFOCENTER3/DRAWER056/GENERAL/DATA0001/00001462.PDF

Pollution Control Department (PCD). (2019). *The National Agenda for action plans "Solving the dust pollution problem" in Thailand 2019*. Pollution Control Department, https://www.pcd.go.th/wp-content/uploads/2021/02/pcdnew-2021-02-18_08-03-46_086635.pdf

Pollution Control Department (PCD). (2021).*Pollution Control Department News*. Pollution Control Department, https://www.pcd.go.th/wp-content/uploads/2021/01/pcdnew-2021-01-20_08-29-15_473417.pdf

Pollution Control Department (PCD). (2022). *MNRE joined hands with partners to study exhaust gas treatment equipment*. Ministry of Natural Resources and Environment Pollution Control Department, https://www.pcd.go.th/wp-content/uploads/2022/05/pcdnew-2022-05-31_09-00-04_645243.pdf

Pollution Control Department (PCD). (2022). *Thailand State of Pollution Report 2021*. Pollution Control Department, https://www.pcd.go.th/publication/26626

Pollution Control Department (PCD). (2022). *The state of air and noise pollution in Thailand 2021*. Thai Pollution Control Department. https://www.pcd.go.th/wp-content/uploads/2022/11/pcdnew-2022-11-01_07-34-54_842781.pdf

PCD. (2022, September). *The Ad Hoc Plan on Solving Dust Pollution Problem in Bangkok 2023.* Pollution Control Department. https://www.opsmoac.go.th/kamphaengphet-dwl-files-451991791285

Pollution Control Department (PCD). (2023). *history concentration of PM2.5 on average 24 hrs.* Pollution Control Department, http://air4thai.pcd.go.th/webV2/history/

Pollution Control Department (PCD), Chulabhorn Research Institute, and Department of Health. (2018). *Air quality assessment for health and environmental policies in Thailand* . Pollution Control Department. https://www.pcd.go.th/wp-content/uploads/2021/10/pcdnew-2021-10-28_04-12-33_133858.pdf

Peckham, S. E. (2012). WRF/Chem version 3.3 user's guide. *National Oceanic and Atmospheric Administration*. https://repository.library.noaa.gov/view/noaa/11119/noaa_11119_DS1.pdf

Phanich, P. (2022). *Quantifying Benefit-Cost Ratios for a Low Emission Zone against Heavy Duty Diesel Vehicles in the Bangkok Metropolitan Region* (Doctoral dissertation, Harvard University). https://nrs.harvard.edu/URN-3:HUL.INSTREPOS:37371538

Prof. Muhammad Bilal. (2021). *Air Quality Monitoring using Satellite Remote Sensing*. Capacity Development Program on Air Quality Management and Emission Reduction of PM2.5 for Asian Countries: http://www.rrcap.ait.ac.th/apn/Documents/P3_AQM_Satellite.pdf

Petroleum Authority of Thailand (PTT). (2023). *PTT NGR : PTT Natural Gas Retail*. https://pttngr.pttplc.com/About/AboutUs?ID=about1

Ren, X., Jiang, N., Li, Y., Lu, W., Zhao, Z., & Hao, L. (2022). Application of Remote Sensing Methodology for Vehicle Emission Inspection. *Atmosphere*, *13*(11), 1862. https://doi.org/10.3390/atmos13111862

Rosenthal, J. (2015). The real challenge for cookstoves and health: more evidence. *EcoHealth*, *12*(1), 8-11. https://link.springer.com/article/10.1007/s10393-014-0997-9

Secretariat for the Acid Deposition Monitoring Network in East Asia (EANET). (2022). *Issues of LCS and Efforts Against the Issues: Thailand's Experiences*. EANET Seminar on Expanding Monitoring System using Low-Cost Sensor (LCS). https://www.eanet.asia/wp-content/uploads/2022/08/Dr.-Supat-Wangwongwatana-Issues-of-LCS-and-efforts-against-the-issues-Thailand-experiences-compressed.pdf

Secretariat for the Acid Deposition Monitoring Network in East Asia (EANET). (2023a). *Event Report*. The EANET Awareness Workshop in 2023. https://www.eanet.asia/wp-content/uploads/2023/06/Awareness-Workshop-2023-Event-Report-_compressed.pdf

Secretariat for the Acid Deposition Monitoring Network in East Asia (EANET). (2023b). *Introduction to Low-Cost Sensors (LCS)*. The EANET Regional Awareness Workshop in 2023. https://www.eanet.asia/wp-content/uploads/2023/06/6-General-Lecture-LCS-Dr.Yuba_.pdf

Shrestha, R. M., Kim Oanh, N. T., Shrestha, R. P., Rupakheti, M., Rajbhandari, S., Permadi, D. A., ... & Iyngararasan, M. (2013). Atmospheric brown clouds: Emission inventory manual. https://www.researchgate.net/publication/260423256_Atmospheric_Brown_Clouds_Emission_Inventory_Manual

Siemens Energy. (2023). *Predictive Emission Monitoring System (PEMS)*. Siemens Energy. https://www.siemens-energy.com/global/en/offerings/services/digital-services/predictive-emission-monitoring-system.html

Signer, M. (2016). *Euro VI*. CDMX Workshop. https://theicct.org/sites/default/files/2016_09%20Mexico%20Euro%20VI%20SIGNER.pdf

Signer, M. (2018). *Euro VI World Class Emission Standards: Regulatory Implications*. msco. https://theicct.org/sites/default/files/0900%20Meinrad%20Signer%20SKYPE%20Buenos%20Aires%2027_09_2018%20Signer_01.pdf

Sirichotpundit, P., Poboon, C., Bhanthumnavin, D., & Phoochinda, W. (2013). Factors affecting energy consumption of households in Bangkok metropolitan area. *Environment and Natural Resources Journal*, *11*(1), 31-40. https://www.thaiscience.info/journals/Article/ENRJ/10892142.pdf

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D., Duda, M. G., … Powers, J. G. (2008). *A Description of the Advanced Research WRF Version 3* (No. NCAR/TN-475+STR). University Corporation for Atmospheric Research. doi:10.5065/D68S4MVH

Stedman, D. H., & Bishop, G. A. (1990). An analysis of on-road remote sensing as a tool for automobile emissions control. Final Report to the Illinois Department of Energy and Natural Resources, https://digitalcommons.du.edu/cgi/viewcontent.cgi?article=1007&context=feat_publications

Sukitpaneenit, M., & Stettler, M. (2019). High spatial resolution traffic flow and emissions based on taxi GPS data in Bangkok, Thailand. In *Proceedings of the ERSA* (p. 405). https://az659834.vo.msecnd.net/eventsairwesteuprod/production-ersa-public/441712b3b60f48528d04fede920493dd

Suwanthada, P. (2022). *Air pollution control from transport and industrial sector*. Center for Clean Air Solutions (CCAS). http://www.ccas.or.th/knowledge

ThaiHealth Official. (2022, January 20). *Clean Air Model in The Pathumwan District*. https://www.thaihealth.or.th/?p=219970

thaipost. (2020). *development of low-cost sensor to measure PM2.5 and solve pollution*. https://www.thaipost.net/main/detail/83652

The Nation. (2022). *Bangkok's new fleet of electric buses is ready to hit the road*. https://www.nationthailand.com/thailand/general/40022489

The Nation. (2023a). *Plugging into the future with EV mobility*. https://www.nationthailand.com/specials/40015527

The Nation. (2023b). *Thai Smile Bus aims to widen its electric bus routes this year*. https://www.nationthailand.com/thailand/general/40025374

theo-courant. (2022). *Bangkok - Chao Phraya: transport by electric ferry*. https://theo-courant.com/en/bangkok-ferry-electric/

Thomas, E., Wickramasinghe, K., Mendis, S., Roberts, N., & Foster, C. (2015). Improved stove interventions to reduce household air pollution in low and middle-income countries: a descriptive systematic review. *BMC Public Health*, *15*, 1-15. https://link.springer.com/article/10.1186/s12889-015-2024-7

Thuamkred P. et al. (2020). Legal Measures on Air Pollution from Large Industrial Plants in Thailand that Generate Small Dust Particles PM 2.5. Retrieved from Faculty of Law, Sukhothai Thammathirat Open University, Rajapark Journal: https://so05.tci-thaijo.org/index.php/RJPJ/article/download/246896/168231

Trilles, S., Vicente, A. B., Juan, P., Ramos, F., Meseguer, S., & Serra, L. (2019). Reliability validation of a low-cost particulate matter IoT sensor in indoor and outdoor environments using a reference sampler. *Sustainability*, *11*(24), 7220. https://doi.org/10.3390/su11247220

United Nations Environment Programme (UNEP). (2011). *Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-lived Climate Forcers*. A UNEP synthesis report. http://www.unep.org/pdf/Near_Term_Climate_Protection_&_Air_Benefits.pdf

United Nations Environment Programme (UNEP). (2023). *EMC: Continuous Emission Monitoring Systems*. United States Environmental Protection Agency. https://www.epa.gov/emc/emc-continuous-emission-monitoring-systems

Watkiss, P., Allen, J., Anderson, S., Beevers, S., Browne, M., Carslaw, D., ... & Young, T. (2003). London low emission zone feasibility study phase II: final report to the London low emission zone steering group. *AEA Technology Environment. https://content.tfl.gov.uk/phase-2-feasibility-summary.pdf*

Winijkul, E., & Bond, T. C. (2016). Emissions from residential combustion considering end-uses and spatial constraints: Part II, emission reduction scenarios. *Atmospheric Environment*, *124*, 1-11. https://doi.org/10.1016/j.atmosenv.2015.10.011

Winijkul, E., Kingkaew, S., & Paijityotee, K. (2023). *Contribution of Inside and Outside-city Air Pollution Sources to The PM2.5 Concentration in Bangkok.* National Research Council of Thailand (NRCT).

Yawootti, A., Panta, S., Wimonthanasit, P., Chaithanu, K., & Thinnakorn, J. (2019). *The Study of Low-Cost Optical Sensor for Air Bourn Particulate Matter Monitoring*. The 3rd National Conference on Informatics, Agriculture, Management, Business Administration, Engineering, Science and Technology. https://www.researchgate.net/publication/325484370_The_Study_of_Low-Cost_Optical_Sensor_for_Air_Bourn_Particulate_Matter_Monitoring_karsuksasensexrhlakkarthangsaengrakhathuksahrabngantrwcwadfunlaxxngnixakas

Zusman, E., Dickella Gamaralalage, P. J., Hengesbaugh, M., Yagasa, R., Hotta, Y., Onogawa, K., ... & Feng, X. (2018). Summary: Air Pollution in Asia and the Pacific-Science-based Solutions. https://www.ccacoalition.org/en/content/air-pollution-measures-asia-and-pacific