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Trend Analysis of Air Quality Index (AQI) and Greenhouse Gas (GHG) Emissions in Taiwan and Their Regulatory Countermeasures

Wen-Tien Tsai * and Yu-Quan Lin

Graduate Institute of Bioresources, National Pingtung University of Science and Technology, Pingtung 912, Taiwan; wsx55222525@gmail.com
* Correspondence: wttsai@mail.npust.edu.tw; Tel.: +886-8-770-3202

Abstract: A reduction in the energy-related emissions of air pollutants would not only mitigate climate change but would also improve local air quality and public health. This paper aimed to analyze the trends of air quality index (AQI) and greenhouse gas (GHG) emissions in Taiwan by using the latest official statistics. In addition, this study also summarized regulatory measures for controlling air pollution from the energy sector with relevance to sustainable development goals (SDGs). With the joint efforts by the public and private sectors, the change in the total GHG emissions did not vary much with the exception of 2009, ranging from 250 to 272 million metric tons of CO_2 equivalent from 2005 through 2019. Based on the data on AQI, the percentage of AQI by station-day with AQI > 100 has decreased from 18.1% in 2017 to 10.1% in 2020, indicating a decreasing trend for all criteria air pollutants. On the other hand, the coronavirus disease (COVID-19) lockdown, in 2019, has positively impacted Taiwan's urban air quality, which was consistent with those observed in other countries. This consistent situation could be attributed to the climate change mitigation policies and promotional actions under the revised Air Pollution Control Act and the Greenhouse Gas Reduction and Management Act of 2015. In response to the SDGs launched by the Taiwan government in 2018, achieving the relevant targets by 2030 can be prospective.

Keywords: greenhouse gas emission; air quality index; trend analysis; climate change mitigation; sustainable development goal

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1. Introduction

Global warming in connection with the anthropogenic emissions of greenhouse gases (GHG) has been recognized by the Kyoto Protocol in 1997. More seriously, extreme climate events such as heatwaves, tropical cyclones, and heavy rainfall have made the weather patterns unpredictable, causing disasters and damage. According to the protocol, the target GHG included carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases). At the global scale, about 50 billion metric tons in terms of carbon dioxide equivalents (CO_{2eq}) were emitted from anthropogenic activities each year [1], which mostly came from the energy sector using fossil fuels for the production of electricity, heat, or steam. In this regard, a reduction in the emissions of air pollutants from energy, transportation, and industry would not only mitigate climate change but would also improve local air quality and public health.

It is well known that burning fossil fuels release both air pollutants and GHG (i.e., CO_2, CH_4, and N_2O). These air pollutants like ozone (O_3) and particulate matter (PM) also involve global warming because they are also climate-relevant and thus known as short-lived climate pollutants (SLCPs) [2–8]. For example, ozone is a powerful oxidant and thus plays a vital role in the formation of photochemical compounds like peroxyalkyl nitrates (PAN) [9]. The health effects of PM (especially in fine PM, or called $PM_{2.5}$), ozone, and its resulting chemicals are closely connected with the lung functions and respiratory system [10,11]. In addition, black carbon, a component of PM, may cause local warming or cooling if it deposits on ice and snow, or suspends in the air. Poor air quality is also caused by the combustion products of fossil fuels, including nitrogen oxides, methane, and other volatile organic compounds (VOCs). By photochemical reactions, these air pollutants will combine in the troposphere to form ozone [9]. As mentioned above, climate change and air pollutants share common sources, implying that reducing air pollution (or improving air quality) and mitigating climate change in an integrated way would be the most effective approach [12–15].

In Taiwan, the central competent authority (i.e., Environmental Protection Administration, abbreviated as TEPA) is responsible for the issues of air quality and climate change. According to the Greenhouse Gas Reduction and Management Act of 2015 [16], the TEPA should submit the National Inventory Report (NIR) each year in response to climate change mitigation and adaptation. Furthermore, the National Climate Change Action Guidelines and Greenhouse Gas Reduction Action Plan shall develop with the considerations of the economy, energy supplies, environments, international situation, and the assignment of responsibilities by the relevant central government agencies. On the other hand, the TEPA shall take control of measures for reducing the emissions of air pollutants from stationary and mobile pollution sources based on the Air Pollution Control Act recently revised in 2018 [16]. These air pollutants are closely related to air quality, which is beneficial to public health.

Obviously, air quality and climate change exist in their interconnected relationship with each other through complex interactions in the atmosphere. Regarding the interactive trend analysis of air quality and climate change in Taiwan, few discussions on the issue were thus addressed in the academic journals. In a study by Liu et al. [17], they investigated the sensitivity of ground-level ozone concentrations to temperature variation in Taiwan using multiple regression models, indicating a positive correlation between ozone sensitivity and temperature. In order to improve air quality by planting trees, Wang et al. [18] reported the benefits of air quality enhancement zone establishments in Taiwan, including CO_2 capture, carbon storage, and global warming mitigation. On the other hand, Li et al. [19] evaluated the prospective impacts of electric vehicle (EV) penetration on the air quality in Taiwan because the traditional fuel-based vehicles greatly contributed to the emissions of criteria air pollutants. It was also found that ambient air pollutants (i.e., CO and NO_2) and temperature were positively associated with dry eye disease [20]. On the other hand, the coronavirus disease (COVID-19) lockdown, in 2019, has positively impacted urban air quality, thus indicating a better ambient air quality in various countries like China [21], India [22], South Korea [23], UK [24], and USA [25]. Some researchers recently investigated the relationship between (renewable) energy consumption, air pollution concentration (e.g., NO_2), and economic growth during the COVID-19 pandemic through a model of artificial neural networks (ANN) [26–28]. For instance, the study by Mele and Magazzino [27] confirmed the causal link between $PM_{2.5}$, CO_2, NO_2, and COVID-19 deaths for 25 major Indian cities. Regarding the impact of the COVID-19 outbreak on AQI in 2020, it may be not discussed yet in the literature.

Therefore, this paper is structured around three key issues. First, we addressed the trend analysis of air quality index (AQI) and GHG emissions in Taiwan, which was extracted from the official (TEPA) data from the Taiwan Air Quality Monitoring Network and the NIR, respectively. In addition, the record changes in air quality in 2020 due to the COVID-19 crisis were preliminarily addressed in the present study. Second, the regulatory countermeasures for air quality management in recent years for coupling with GHG emission mitigation during this period were summarized and discussed. Finally, this work will provide valuable policy implications for the TEPA due to the promulgation of the Air Pollution Control Act and other public policy issues, including global warming, GHG emission standards, and revised AQI for $PM_{2.5}$. In response to the sustainable development goals (SDGs) announced by the United Nations (UN) in 2015 [29], the Taiwan SDGs for air quality and climate change mitigation by 2030 was compiled to show the Taiwan government's policy blueprint under the efforts of central competent authorities.

2. Data Mining and Methodology

In this work, the main purposes were to analyze the trend of air quality index (AQI) and relevant GHG emissions in Taiwan. Using these trend variations, the sustainable development goals in Taiwan were further summarized to align with the Taiwan government's efforts in improving air quality and mitigating GHG emissions from the energy sector. The statistical data and regulatory policies are briefly summarized below.

2.1. AQI in Taiwan

In the early 1990s, the Taiwanese Environmental Protection Administration (TEPA) established the Taiwan Air Quality Monitoring Network, which collected the information and data regarding the concentrations of criteria air pollutants (i.e., PM_{10}, $PM_{2.5}$, CO, SO_2, NO_2, O_3, and non-methane hydrocarbons) and meteorological parameters. At the end of 2020, the TEPA set up 85 air quality observation stations nationwide for the network. The principles of observation instruments in the network include CO by non-dispersive infrared, SO_2 by ultraviolet fluorescence, NO_2 by chemiluminescence, O_3 by ultraviolet absorption, hydrocarbons by flame ionization detector, and $PM_{10}/PM_{2.5}$ by screening device and mass calculation. In order to ensure the accuracy and reliability of the data provided by the network, the TEPA referred to the Quality Assurance (QA) program of the US EPA, which was incorporated into the design of the observation network. According to the QA program, the air quality observation stations conducted monthly checks and an annual performance check on its pollutant analysis instruments to achieve the Data Quality Objectives (DQO) of accuracy (deviation) within $\pm$15% and $\pm$10% for gaseous air pollutants and particulates (PM_{10} and $PM_{2.5}$), respectively. In addition, this network has been operating for about thirty years and its data are open to the public. The updated data on the statistics and status of AQI in Taiwan were obtained from the official yearbook [30] and the website of the central competent agency (i.e., TEPA) [31].

2.2. Inventory of GHG Emissions from the Energy Sector

Taiwan's statistics on GHG emissions were compiled from the updated NRI, which was based on the methodology by the Intergovernmental Panel on Climate Change (IPCC) [32]. In this work, the updated NIR was used to analyze the trends of total emissions of CO_2, CH_4, and N_2O and their major sources since 2005 [33].

2.3. Regulatory Measures for Controlling the Emissions of Air Pollutants and Relevant GHG

The relevant information about the regulatory measures for improving air quality and also mitigating the emissions of GHG from the energy sector was based on the laws by accessing the official website [16]. The most relevant laws included the Air Pollution Control Act and the Greenhouse Gas Reduction and Management Act, which are executed by the TEPA and local governments.

3. Results and Discussion

3.1. Trend Analysis of Air Quality Index (AQI)

3.1.1. Air Quality Standards in Taiwan

According to Article 5 of the Air Pollution Control Act, the central competent authority (i.e., TEPA) in consultation with relevant agencies shall announce the air quality standards (AQS) [16]. These standards need to be reviewed every four years based on the current air quality levels in Taiwan, the improvement plans of the government, and the standard-setting trends of developed countries. In this regard, Taiwan's AQS was first announced on 10 April 1992, and subsequently revised four times (21 July 1999; 13 October 2004; 14 May 2012; 18 September 2020). In the revised AQS in 2020, the TEPA eliminated the standard for total suspended particulates (TSP) and also revised stricter standards for suspended particle (PM_{10}, particles with a diameter of less than 10 μm), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and lead. For instance, the maximum one-hour average concentration of SO_2 was lowered from 250 ppb to 75 ppb and the maximum annual average concentration from 30 ppb to 20 ppb. Table 1 listed the levels of AQS in Taiwan.

Table 1. Ambient air quality standards in Taiwan.

Pollutant		Averaging Time	Level
Particle matter (PM)	$PM_{2.5}$	24 h [1]	35 μg/m^3
		1 year [2]	15 μg/m^3
	PM_{10}	24 h or 1 day [3]	100 μg/m^3
		1 year	50 μg/m^3
Sulfur dioxide (SO_2)		1 h [4]	0.075 ppm
		1 year	0.02 ppm
Nitrogen dioxide (NO_2)		1 h	0.1 ppm
		1 year	0.03 ppm
Carbon monoxide (CO)		1 h	35 ppm
		8 h [5]	9 ppm
Ozone (O_3)		1 h	0.12 ppm
		8 h	0.06 ppm
Lead (Pb)		Rolling 3-month average [6]	0.15 μg/m^3

[1] Continuous sampling for 24 h. [2] Arithmetic average of the average of each day within one year. [3] Arithmetic average of the average of each hour within one day. [4] Arithmetic average of each measured value within one hour. [5] Arithmetic average of the average of each hourly measured value in a consecutive 8 h. [6] Arithmetic average of the average of valid data for three consecutive months.

3.1.2. Trend Analysis of Air Quality Index (AQI) in Taiwan

In order to communicate with the public regarding the healthy conditions of ambient air quality, the central competent authority (i.e., TEPA) shall issue the AQI daily based on the data from 77 air quality monitoring stations. In Taiwan, the AQI shall be calculated as follows: the concentrations of ozone (O_3), fine suspended particulates ($PM_{2.5}$), suspended particulates (PM_{10}), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) in a day are converted into their corresponding sub-indicators based on their impacts on human health by six scales [34–37]. The largest value of the sub-indicators is the AQI of the monitoring station on the day. Table 2 listed the scaled levels of AQI and their corresponding colors that are easy for the public in Taiwan to understand.

Table 2. Scaled levels of Taiwan's air quality index (AQI) and corresponding colors.

AQI (Scale/Color)	O_3 (ppm)		$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)	CO (ppm)	SO_2 (ppm)	NO_2 (ppm)
Statistical methods	8 h	Real-time	12 h [1]	12 h [1]	8 h	Real-time	Real-time
Good (0–50/Green)	0.000–0.054	-	0.0–15.4	0–54	0–4.4	0–35	0–53
Moderate (51–100/Yellow)	0.055–0.070	-	15.5–35.4	55–125	4.5–9.4	36–75	54–100
Unhealthy for sensitive groups (101–150/Orange)	0.071–0.085	0.125–0.164	35.4–54.4	126–254	9.5–12.4	76–185	101–360
Unhealthy (151–200/Red)	0.086–0.105	0.165–0.204	54.5–150.4	255–354	12.5–15.4	186–303	361–649
Very unhealthy (201–300/Purple)	0.106–0.200	0.205–0.404	150.5–250.4	355–424	15.5–30.4	305–604	650–1249
Hazardous (301–500/Maroon)	-	0.405–0.604	250.5–500.4	425–604	30.5–50.4	605–1004	1250–2049

[1] 0.5 × average of the first 12 h + 0.5 × average of the first 4 h.

In Taiwan, the air quality can be affected by several reasons, including rapid urbanization, industrial pollution sources, coal-fired power plants, meteorological conditions, numerous motor vehicles, and foreign pollution sources (e.g., dust storm from China). Many regulations and administrative measures have been taken by the TEPA in the past two decades. Table 3 listed the data on the annual average concentrations of suspended particulates (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3) during the period of 2014–2020 [30]. Except for O_3, it indicated a decreasing trend for all air pollutants with relevance to Taiwan's AQI. As listed in Table 3, the annual average concentrations of O_3 decreased from 58.36 ppb in 2014 to 53.89 ppb in 2016, but increased to 56.43 ppb in 2017 and then indicated a decreasing trend from 2017 to 2020. This result was similar to the characterization of the AQI from 2015 to 2017 in Southwestern Taiwan [38]. The inconsistent trend could be attributed to the sunshine UV radiation and global warming (average temperature rise), thus leading to the variations in the O_3 concentrations. In order to coincide with the new AQI adopted in December 2016, Table 4 summarizes the statistics of AQI by station-day from 2017 to 2020 [30]. The statistics in 2020 for Taiwan's AQI showed that the percentage of days with AQI > 100 (indicating poor air quality) was 10.1%, while the percentage of days with good air quality was 54.20%. Based on the data trend in Tables 3 and 4, the impact of COVID-19 on ambient air quality in Taiwan was not subject to economic or mobility restrictions. Consistently, the statistics showed that the percentage of AQI by station-day with AQI > 100 has decreased from 18.1% in 2017 and 16.0% in 2018 to 13.1% in 2019. As studied by Maurer et al. [39], they confirmed the air quality improvement (PM_{10}) in the cities of Taiwan from 1985 to 2016, causing a better trend in visibility. Cheng and Hsu [40] also indicated an apparent decline in the data on NO_2, SO_2, and $PM_{2.5}$ concentrations from 2006–2017, supporting the positive effect on air quality improvement by emission control measures with the promulgation of the Air Pollution Control Act in Taiwan. These figures clearly indicated that the nation's air quality has been greatly improved in recent years due to the successful efforts for stationary and mobile air pollution control. For example, the vigorous implementation of the Air Pollution Control Action Plan by the TEPA during this period has led to boiler replacements (i.e., changing from liquid fuels to natural gas), smoke control equipment installation for the food and beverage industry, less or less widespread burning of joss paper, audits and controls for construction projects, promotion of electric vehicle, smoke filtration equipment installation on diesel-engined vehicles, and other measures for reducing fugitive air pollution (e.g., fugitive dust control in riverside areas) and open-burning incidents. These measures for improving air quality will be subsequently summarized in Section 3.3. These improved AQI results were empirically consistent with the statistical data on the public nuisance petition cases by air pollutants (excluding unusual smell pollutants). The number by petitioning for air pollutants showed a declining trend in the past decade, decreasing from 15,015 cases in 2010 to 10,725 cases in 2020 [30].

Table 3. Anual average concentrations of fine suspended particulates ($PM_{2.5}$), suspended particulates (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and ozone (O_3) during the period of 2014–2020 in the Taiwan area [1].

Year	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)	SO_2 (ppb)	CO (ppm)	NO_2 (ppb)	O_3 (ppb) [3]
2014	– [2]	52.0	3.40	0.41	14.37	58.36
2015	–	47.1	3.13	0.40	13.62	56.13
2016	–	42.9	2.97	0.39	13.53	53.89
2017	20.5	44.0	2.88	0.35	12.86	56.43
2018	19.0	42.6	2.71	0.35	12.20	55.34
2019	17.3	35.7	2.30	0.35	11.57	54.91
2020	15.1	30.1	2.14	0.31	10.73	54.77

[1] Source [30]. The data from the monitoring stations less than 6000 h were not included in calculating the annual average concentration. [2] Not available for the measurement data. [3] Average of daily hourly highest values.

Table 4. Status of Taiwan's air quality index (AQI) in recent years (2017–2020) [1].

Year	Total Station-Day	AQI by Station-Day (Percentage)					
		Good (0–50)	Moderate (51–100)	Unhealthy for Sensitive Groups (101–150)	Unhealthy(151–200)	Very Unhealthy (201–300)	Hazardous (301–500)
2017	21,876	8690 (39.72)	9231 (42.20)	3334 (15.24)	610 (2.79)	11 (0.05)	0 (0.00)
2018	21,885	9299 (42.49)	9083 (41.50)	2955 (13.50)	540 (2.47)	8 (0.04)	0 (0.00)
2019	21,775	10,423 (47.87)	8543 (39.23)	2423 (11.13)	383 (1.76)	3 (0.01)	0 (0.00)
2020	21,958	11.902 (54.20)	7845 (35.73)	1976 (9.00)	225 (1.03)	10 (0.04)	0 (0.00)

[1] Source [30].

3.2. *Trend Analysis of Greenhouse Gas Emissions with Relevance to Air Quality*

Based on the report by the International Energy Agency (IEA) [41], the energy sector is the most important sector in the inventories of GHG emissions for most countries or regions. In Taiwan, the central competent authority (i.e., TEPA) shall establish strategies to mitigate GHG emissions according to the Greenhouse Gas Reduction and Management Act passed in July 2015. In this regard, the TEPA must publish the NIR periodically on its website for free downloading. Based on the latest NRI [33], more than 90% of GHG emissions came from the energy sector, which mainly included energy industries, industrial manufacturing & construction industries, and transportation. Therefore, the mitigation strategies and actions for mitigating the emission of GHG from the energy sector become more important and urgent because the accompanying combustion pollutants (i.e., particulate matters, SO_2, NO_2, CO) emitted from the stationary sources and mobile sources are relevant to the air quality. In this regard, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are responsible for the GHG emissions in the energy sector due to the fuel combustion for heat, steam, electricity, or transportation. Table 5 listed the variations in the emissions of CO_2, $CH_{4,}$ and N_2O in Taiwan's energy sector since 2005. In terms of the major sources in the energy sector [33], Table 6 further showed their total emissions of CO_2, $CH_{4,}$ and N_2O from the energy industries, industrial manufacturing & construction industries, transportation, and other sources [33], which were depicted in Figure 1 to see the variations since 2005.

Based on the data in Tables 5 and 6, the important features were briefly addressed as follows:

1. During the period of 2005–2019, the change in the total emissions did not vary much with the exception in 2009, ranging from 249.9 to 269.1 $MtCO_{2eq}$. An increase of 7.68% in the GHG emission was obtained at an average annual growth rate of 0.57%. The total GHG emission in 2018 was slightly lower than the previous year by 0.88%. This stable situation was mainly due to the regulatory measures and promotional actions, including renewable energy development, improvement of energy efficiency, and energy conservation [42–44]. For example, the electricity generation by renewable energy sources significantly increased from 7808 GWh in 2009, to 15,247 GWh in 2019 [45]. Herein, the data in 2019 were estimated by the authors based on the energy statistics in 2019 [45].
2. In terms of the emission sources in the energy sector, the contribution percentage of GHG emissions from the energy (electricity generation from power plants using fossil fuels) industry indicated a slight increase from 62.8% in 2005, to 70.6% in 2018. On the other hand, the contribution percentages of GHG emissions from the industrial manufacturing & construction industries, transportation, and other sources showed a decreasing trend.
3. Among these sources in the energy sector, the contribution percentage of GHG emissions from the industrial manufacturing and construction industries significantly reduced from 42.9 $MtCO_{2eq}$ in 2005, to 32.8 $MtCO_{2eq}$ in 2019. This decline should be attributed to the industrial policy for shifting to high-tech industries and energy management policy for enhancing energy efficiencies during this period. For example, the data on energy intensity decreased from 6.38 in 2005, to 4.44 L of oil equivalent per NT$1000 (about US$35) in 2019 [45].

Table 5. Taiwan's GHG emissions from the energy sector since 2005 [1].

GHG	Year										
	2005	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019 [2]**
Carbon dioxide (CO_2)	248.0	251.7	257.1	253.2	254.1	258.5	258.5	263.0	269.5	267.1	258.7
Methane (CH_4)	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Nitrous oxide (N_2O)	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3
Total emission	249.9	253.6	259.0	255.1	256.0	260.4	260.4	265.0	271.5	269.1	260.7

[1] Source [45]; unit: 10^6 metric tons based on CO_2 equivalent. [2] Estimated.

Table 6. Taiwan's GHG (CO_2/CH_4/N_2O) emissions from various sources in the energy sector since 2005 [1].

GHG	Year										
	2005	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019 [2]**
Energy industry	157.0	166.2	170.6	169.0	169.0	175.9	175.9	179.3	187.9	189.9	182.0
Manufacturing industry & construction	42.9	41.6	42.5	41.2	42.2	39.2	38.3	38.5	36.9	33.6	32.8
Transportation	37.7	35.4	35.9	35.1	35.0	35.4	36.3	37.4	37.0	36.0	36.2
Other sources	12.3	10.4	10.0	9.8	9.8	9.9	9.9	9.8	9.7	9.6	9.7
Total	249.9	253.6	259.0	255.1	256.0	260.4	260.4	265.0	271.5	269.1	260.7

[1] Source [45]; unit: 10^6 metric tons based on CO_2 equivalent. [2] Estimated.

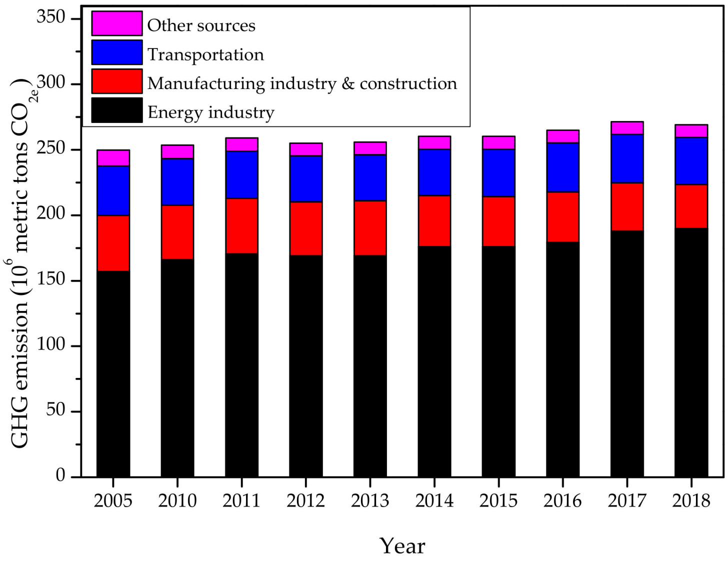

Figure 1. Variations on Taiwan's GHG emissions from various sources in the energy sector [45].

3.3. *Air Quality Management Measures for Combating Climate Change in Taiwan*

Based on the trend analysis in Section 3.1, Taiwan's AQI for the percentage of days with AQI > 100 showed a decreasing trend, while the percentage of days with good air quality was increased. These figures clearly indicated that the current status of air quality in recent years has been greatly improved and that efforts to control air pollution have paid off. In addition, the findings from this work have provided valuable policy implications for the TEPA due to the promulgation of the Air Pollution Control Act. In Taiwan, the legal framework for air quality management is based on the act, which was enacted to control ambient air pollution, maintain the living environment and public health, and enhance the quality of life. This act was first promulgated in May 1975, and subsequently revised several times because the nature of air pollution control engenders continual public policy issues, including global warming, GHG emission standards, revised AQI for $PM_{2.5,}$ and health-oriented regulations. In recent years, the public is increasingly concerned about the impact of air quality on health. According to the latest amendment in August 2018, the TEPA was authorized more efforts on the exposure to PM (PM_{10} and $PM_{2.5}$) and VOC in a variety of urban areas due to their toxic components. One of the most important issues is to get sufficient data on the exposure-response relationships to adopt adequate emission control measures for these toxic components, including heavy metals, dioxins, and other hazardous air pollutants (HAPs).

According to the act amendment in 2018, the TEPA thus accelerated the total air quantity control plan amendment schedule to facilitate the control measures for mobile sources and stationary sources of air pollution, which will be summarized in the following section [31].

3.3.1. Control Measures for Mobile Sources of Air Pollution

The transportation sector is one of the major GHG emission sources and contributes significantly to urban air pollution quality [46]. In Taiwan, the registered number of motor vehicles on the road has been showing an increasing trend along with economic growth in the past decades. At the end of 2019, the number in Taiwan totaled 22.11 million, including 13.99 million vehicles of motorcycles and 8.12 million automobiles [30]. Compared to the figures in 1991 (7.41 million vehicles of motorcycles and 3.20 million automobiles), it indicated the average annual growth rates of 2.30% and 3.38%, respectively. However, the emissions of combustion products from motor vehicles (i.e., mobile pollution sources) are the main source of air contaminants in urban areas in Taiwan with limited land and a highly dense population, posing a negative impact on air quality and public health. In this regard, the TEPA took the following control measures for curbing the growth of registered motor vehicles and also reducing the emissions of air pollutants from them.

1. New vehicle control measures
   - Phased implementation of stricter vehicle emission standards
   - New vehicle model inspection and testing system in compliance with emission standards
2. On-road vehicle emissions control measures
   - Routine exhaust emissions inspection and testing program
   - Motorcycles and diesel engine automobile spot check
   - Remote sensing of emissions from gasoline engine automobiles
   - Urging the public to identify and report on-road gross polluters or other high-emission vehicles
   - Eliminating old vehicles and two-stroke engine motorcycles
   - Enhancing the quality of exhaust emissions inspection and testing of in-use gasoline and diesel engine automobiles
3. Clean alternative fuel promotion measures
   - Subsidizing the price of liquefied petroleum gas (LPG)
   - Setting control measures of automobile gasoline and diesel fuels (e.g., setting more stringent standards for the sulfur content of automobile fuels)
   - Enforcing the air pollution control fee program
   - Cracking down on illegal fuel
   - Adding more LPG vehicles and LPG filling stations
   - Promoting the use of bio-diesel fuel and ethanol gasoline
4. Low-pollution vehicles promotion measures
   - Advocating the use of low-pollution motorcycles
   - Subsidizing the purchase of electric auxiliary bicycles
   - Promoting the use of hybrid vehicles
   - Advocating bike lanes
   5. Traffic management measures
   - Promoting the use of public transportation
   - Expanding paid motorcycle parking areas
   - Revising the traffic code to curb the growth of motor vehicles
   - Designating clean air zones that prohibit the entry of any motor vehicles

3.3.2. Control Measures for Stationary Sources of Air Pollution

According to the definition of the act, the stationary sources of air pollution refer to the pollution sources which are not able to change location under their own power. Therefore, this could include the vents or stacks in the factories, refineries, boilers, and power plants, emitting a variety of air pollutants. These emitted pollutants may belong to criteria air pollutants and hazardous air pollutants. Under the authorization of the act, the TEPA took the following regulatory measures for controlling the emissions of air pollutants from stationary sources.

- Evaluation of the total quantity control zones
- Stationary pollution source installation and operating permit management
- Air pollution control fee system
- Improved control of fugitive dust pollution sources
- Reinforcing control of dioxins and other hazardous air pollutants
- Boiler replacement subsidy
- Control of volatile organic compounds (VOCs) from consumer products
- Continuous emission monitoring system
- Response to air pollution emergency
- Control, monitoring, and improvement of volatile organic air pollutants

3.4. Sustainable Development Goals for Air Quality and GHG Emissions in Taiwan

In order to provide a target-oriented blueprint for peace and prosperity to all countries in the near future (2030), the United Nations (UN) announced 17 Sustainable Development Goals (SDGs) on 25 December 2015. In 2016, the Taiwan government advanced its efforts by referring to the UN SDGs, including goals for 2030 and targets for 2020. Among these efforts, renewable energy development in the past two decades may be the most significant progress. One of the purposes was to improve air quality in Taiwan [47]. Furthermore, the Taiwan government announced Taiwan's Sustainable Development Goals in July 2019 [48]. Regarding air quality issues, the third goal is "Good Health and Well-being", which involves Target 3.9: "By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination". On the other hand, the 11th goal aims at taking urgent action to combat climate change and its impacts.

3.4.1. Sustainable Development Goals for Air Quality by 2030 in Taiwan

According to Target 3.9.1 ("air quality improvement for maintaining people's health"), in the third goal of Taiwan's SDGs, the baseline (2016) and goals by 2020/2030 were listed in Table 7. It should be noted that the concentrations of sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) have met the Air Quality Standards (AQS) for all counties and municipalities in the baseline year (2016).

Table 7. The goals of Taiwan's SDGs for air quality by 2020 and 2030.

SDG's Targets for Air Quality	Baseline (2016)	2020	2030
Fine suspended particulate matter ($PM_{2.5}$) [1]	20 μg/m^3	15 μg/m^3	12 μg/m^3
	874 times [2]	499 times	140 times
Suspended particulate matter (PM_{10}) [1]	43.5 μg/m^3	37 μg/m^3	35 μg/m^3
Ozone (O_3)	462 times [3]	350 times	140 times
Sulfur dioxide (SO_2)	Meeting AQS [4]	Meeting AQS	Meeting AQS
Nitrogen dioxide (NO_2)	Meeting AQS	Meeting AQS	Meeting AQS

[1] Based on national annual average concentration. [2] ≥54 μg/m^3 based on national daily average concentration in total by all monitoring stations. [3] ≥86 ppb based on national daily maximum 8 h average in total by all monitoring stations. [4] Referred to Table 1.

3.4.2. Sustainable Development Goals for GHG Emissions by 2030 in Taiwan

Under Article 4 of the Greenhouse Gas Reduction and Management Act passed by Taiwan's Congress in 2015 [16], the core target is to reduce GHG emissions to less than 50% of 2005 levels, by 2050. With the promulgation of the act in 2015, the phase control goals were definitely made once every five years. The first period for GHG emission control was set in the range of 2016–2020. The net GHG emission in the previous year (2015) was 263.139 million metric tons in terms of carbon dioxide equivalent (263.139 $MtCO_{2eq}$). On the other hand, the net GHG emission (i.e., 266.038 $MtCO_{2eq}$) in 2005 was set as the baseline level. According to Target 13.2.1 ("Achieving phase control goals of every period for greenhouse gas emissions") in the 13th goal of Taiwan's SDGs [48], the goals by 2020 and 2030 were summarized below.

1. Goals by 2020 According to the first period for GHG emission control goals approved by the Taiwan government in January 2018, the net GHG emissions by 2020 must reduce by 2%, as compared to the baseline year (2016); that is, 260.717 $MtCO_{2eq}$. Furthermore, the goals for the GHG emissions by various sectors were given below:
    - Energy sector: 32.305 $MtCO_{2eq}$ (reduced by 3% compared to the 2005 level).
        - Carbon emission factor: 0.492 kg CO_{2eq}/kWh (exclusive of own use by power plants and line loss).
        - The total installed capacity of renewable energy will be 10,875 MW. In parallel with this, electricity generation will be 25,200 GWh.

- Industrial processes sector: 146.544 $MtCO_{2eq}$ (reduced by 3% compared to the 2005 level).
    - Energy intensity in 2020 (reduced by 43% compared to the 2005 level; that is, 6.83 L of oil equivalent/1000 NT$).
- Transportation sector: 37.211 $MtCO_{2eq}$ (reduced by 2% compared to the 2005 level).
    - Public transport by 2020 will grow more than 7% compared to that of 2015 level.
    - The promotional target for the sales of electric motorcycles during the period of 2018–2020 will increase by 121,000.
- Residential and commercial sector: 57.530 $MtCO_{2eq}$ (reduced by 2.5% compared to the 2005 level).
    - As compared to that in 2017, the building shells of new architects constructed by the design basis levels (e.g., energy saving) will increase by 10%.
    - As compared to that in 2017, the electricity efficiency in the public sector buildings will improve by 5%.
- Agriculture sector: 5.318 $MtCO_{2eq}$ (reduced by 25% compared to the 2005 level).
    - Total organic and friendly farming land area: 15,000 hectares.
    - The biogas-to-power production by valorizing manure with 250×10^4 heads swine (about 50% of total swine heads on farms).
    - The forest land area via afforestation and reforestation: 3636 hectares.

2. Goals by 2030 According to the legal norms under the Greenhouse Gas Reduction and Management Act, the net GHG emission by 2030 must reduce 20% compared to the baseline year (2005). Furthermore, the sector goals for the GHG emissions were described as follows:
    - Energy sector
        - The total installed capacity of renewable energy will be 31,000 MW.
    - Industrial processes sector
        - Energy intensity will be reduced by 50%, compared to the 2005 level.
    - Transportation sector: 37.211 $MtCO_{2eq}$ (reduced by 2% compared to the 2005 level).
        - Public transport will grow more than 20% compared to that of 2015 level.
        - Official vehicles and city buses will be electrified totally.
        - Motorcycles using new energy accounted for 35% of new sales.
    - Residential and commercial sector: 57.530 $MtCO_{2eq}$ (reduced by 2.5% compared to the 2005 level).
        - The electricity efficiency in the public sector buildings will improve by 10% and meet the announced specifications of the energy usage index (EUI).
        - Planning for the establishment of building energy database and the development of building energy passport.
    - Agriculture sector
        - Total organic and friendly farming land area: 30,000 hectares.
        - The biogas-to-power production by valorizing manure with 375×10^4 heads swine (about 75% of total swine heads on farms).
        - The forest land area via afforestation and reforestation: 7080 hectares.
    - Waste management sector
        - The national sewage treatment rate will reach 70%.

4. Conclusions and Prospects

As a member of the global village, Taiwan has actively taken part in the international response to climate change in the past three decades. In this paper, the trend analyses of AQI and GHG emissions in Taiwan's energy sector were carried out. It was revealed that the total GHG emissions seemed to show no more increase since 2005, showing a decoupling trend between the air pollution emission and the economic growth. Based on the data on AQI, the percentage of AQI by station-day with AQI > 100 has decreased from 18.1% in 2017, to 10.1% in 2020 (the year of COVID-19), indicating a decreasing trend for all criteria air pollutants. In addition, the findings from this work have provided valuable policy implications for the TEPA due to the promulgation of the Air Pollution Control Act. In 2018, the act was revised to adopt continual regulatory policy measures, including global warming, GHG emission standards, revised AQI for $PM_{2.5,}$ and health-oriented regulations. More significantly, the TEPA was authorized more efforts on the exposure to PM (PM_{10} and $PM_{2.5}$) and VOC in a variety of urban areas due to their toxic components like heavy metals, dioxins, and other hazardous air pollutants (HAPs). In line with the sustainable development goals (SDGs) launched by the Taiwan government in 2018, the central competent agency (i.e., TEPA) set the SDGs of air quality and net GHG emissions by 2020 and 2030. Although the COVID-19 has caused global, multi-dimensional effects, including economic activities, lifestyle patterns, air quality, and public health, its impacts in Taiwan were not significant in 2020. Therefore, achieving the relevant SDGs can be prospective in the near future.

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