Analysis of Air Quality and Health Co-Benefits under Low Carbon Pathway in Taiwan

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ABSTRACT

Climate change has been proven to have adverse effects on human health and ecosystems, especially, the continuous increase in greenhouse gas emissions that are able to drive extreme weather events around the world. Besides greenhouse gas emissions and air pollution also have a mutual relationship. The PM2.5 concentration has been decreasing year by year, but the ozone concentration has been slowly increasing, indicating that ozone issues will be a focus of concern in Taiwan in the future. Therefore, this study focuses on air pollution and its health impacts on power generation on climate change scenario. The air quality in 2050 was estimated in this study by using the Long-range Energy Alternatives Planning System (LEAP) model and the Weather Research and Forecasting-Community Multiscale Air Quality Modeling (WRF-CMAQ) system. The future power plants’ emissions were calculated by historical inventory and the power generation from 2010 to 2016. The simulation results revealed the low-carbon path in the electricity industry can lead to some improvements in air quality and also the associated health benefits. This study demonstrates that implementing carbon reduction strategies in the power sector would lead to a slight increase in ozone concentration. In detail, the annual PM2.5 concentrations would decrease by 0.7 µg m⁻³ (4%) from BAU (Business As Usual) scenario, while the O3 concentrations would have an increase of 0.3 ppb (1%). The reduction of air pollution can prevent 1012 (374 – 2463) deaths, saving around 48.9 billion NTD in health monetary costs. In the short term, it is projected that there may be a decrease of 45 patients hospitalized due to respiratory diseases and 53 patients hospitalized due to cardiovascular diseases. Moreover, the reductions in the power sector are expected to have more significant impacts in densely populated areas due to their combination of industrial and residential zones.

Keywords: Low-carbon path, Air quality, Health benefit

1 INTRODUCTION

The mitigation of climate change is a global challenge. Climate change has been demonstrated to have adverse effects on human health and ecosystems. Moreover, global warming caused by increased greenhouse gas (GHG) emissions is promoting extreme weather events and affecting food production, water resources, and public health, posing severe threats to human life and property (Kusangaya et al., 2014; Woodward et al., 2014; Maji et al., 2018; Watts et al., 2021).

The 21st Conference of the Parties (COP21) in the United Nations Framework Convention on Climate Change (UNFCCC) reached a historic agreement in Paris to cope with climate change and
unveil actions and investments toward a low-carbon vision and climate-resilient future.

The United Nations Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment Report (IPCC AR6) in February 2022, which stated that global temperature is projected to increase by approximately 1.5°C in the next 20 years and that the world is not immune to an increase in climate hazards, such as extreme climate disasters, heat waves, and biodiversity reduction. These hazards have affected energy, water, and food security, resulting in the loss of many human and natural habitats. In response to the high-risk impact of a global climate emergency, the UN Climate Conference called for more urgent climate action to halve global GHG emissions by 2030 and deliver on the net-zero goal by 2050 to limit global temperature rise to within 1.5°C.

The emissions of many air pollutants exacerbate climate change and have adverse impacts on human health and ecosystems (Grimm et al., 2013, 2016; Gao et al., 2018). According to the World Health Organization (WHO), in 2019, over 99% of the global population lived in areas where the air quality exceeded WHO air-quality guidelines. The effects of outdoor air pollution led to approximately 4.2 million premature deaths in 2019 (WHO, 2022).

Rypdal et al. (2007) evaluated the impact of recent European climate policies on air quality in northern Europe and found that although these policies primarily target CO₂, they may indirectly affect all air pollutants, and thus impact air quality. The study used computable general equilibrium (CGE) models to analyze how emission caps, the expansion of the European Union (EU) Emissions Trading System, carbon taxes, and the participation of Russia and non-EU Eastern European countries after 2012 will impact emissions, the regional environment, and human exposure to particulate matter in the Nordic countries. It was revealed that more stringent targets will help reduce air pollutant emissions and benefit ecosystems and human health (Rypdal et al., 2007).

Taiwan actively participated in COP21 and unveiled its Intended Nationally Determined Contribution (INDC) in September 2015. The INDC set a target to reduce GHG emissions by 50% from the Business-as-Usual (BAU) scenario, based on the estimated development trend in 2013. This means reducing emissions from 428 million tons to 214 million tons. The target is equivalent to a 20% reduction in Taiwan’s 2005 emissions (269 million tons). The 2030 emissions target set by the INDC is a stepping stone towards achieving the long-term goal of reducing emissions to less than 50% of the 2005 level (<134 million tons) by 2050. This 2050 emission reduction target has been incorporated into the Greenhouse Gas Reduction and Management Act, which was promulgated and enacted in July 2015. On Earth Day 2021, Taiwan announced its goal of achieving carbon neutrality by 2050 and that it would actively deploy net-zero carbon emission pathway assessments.

Energy use is the largest source of GHG emissions. According to the assessment by the International Energy Agency (IEA), to achieve a global temperature limit of 2°C by 2050, the global energy intensity in the industrial sector would need to be reduced from USD 174 M/toe (million dollars per ton of oil equivalent) in 2016 to USD 88 M/toe by 2050, representing an overall reduction in energy intensity of approximately 50% (Mead, 2017). Regarding industry sector initiatives, in addition to promoting carbon pricing and reducing technology costs, implementing policies to accelerate the achievement of targets and overcome development barriers is also recommended. This would include adopting energy management systems, developing low-energy-intensive production pathways, supporting industrial equipment efficiency improvement and innovation to reduce carbon costs, and promoting new (ecological) business models (including long-term compensation and offsetting measures).

Energy use affects GHG emissions, and air quality can be greatly affected by the overall atmospheric environment and energy use patterns. Following the net-zero pathway plan for 2050, various factors such as energy usage, electricity consumption, and the development of electric vehicles at different stages will lead to an average annual growth rate of 2.0% ± 0.5% in electricity consumption and negative growth trends in non-electricity consumption, such as of petroleum products, natural gas, and coal. This indicates that in addition to reducing GHG emissions, impacts on the economy, energy supply, air quality, and public health are also benefitted by the implementation of a net-zero pathway. Taiwan’s 2050 net-zero transition pathway planning will involve substantial changes in energy use in the power sector. Coal-fired power generation will move in a low-carbon and zero-carbon direction, promoting the switch from coal to gas, increasing the use of natural gas to reduce the proportion of coal, and building a zero-carbon energy system.
to maximize renewable energy. In addition to energy policies and greenhouse gases (GHGs), climate change scenarios should also be considered as a key factor influencing air pollution when assessing the impact of low-carbon strategies on air quality. According to the key scientific raised in the IPCC AR6 "Impacts, Adaptation, and Vulnerability" and the updated report on the impact assessment of climate change in Taiwan, in the warming scenario, changes in meteorological factors, such as reduced wind, increased stability, and shallower boundary layers, have led to worsening air quality (air quality index > 100) in the western half of Taiwan during winter, particularly in the central and southern regions. Under a warming scenario, atmospheric changes will lead to increased air pollution concentrations. Therefore, it is essential to conduct prior simulations and evaluations on reducing GHG emissions and increasing energy, air quality, and public health benefits through net-zero policies.

This research evaluated the improvement of air quality through a net-zero pathway using the Community Multiscale Air Quality modeling system (CMAQ), and its chemical transport mechanism was calculated based on input meteorological data. CMAQ simulates the changes in air quality and subsequent health exposure level of the population under different climate change scenarios. Air pollution caused by energy generated from fuel combustion is a major factor affecting the incidence of diseases and deaths among the general public, particularly among those living in poverty, who tend to use lower-quality energy and technology. As the carbon dioxide emitted during energy production also has an impact on global climate change, in recent years, global warming caused by carbon dioxide has become a major issue for all countries. With air pollution and global warming being two major threats to human health and political stability, countries are committed to developing alternative energy sources and improving energy efficiency to mitigate the impact of air pollution.

He et al. (2001) estimated that if China implements proactive energy policies (including climate-related policies to improve energy structure and efficiency, as well as pollution reduction policies to control air pollutant emissions arising from energy consumption), it can both improve energy efficiency and air quality and bring considerable health benefits. Their assessment indicates that if the energy-related policies proposed by China at this stage are actively implemented, substantial energy, environmental, and economic benefits will be achieved by 2030, with a reduction of 1469 million tons of CO₂ emissions, a 12–32% reduction in the concentration of air pollutants in the local environment, and over USD 100 billion in health benefits (He et al., 2010).

The relationship between air quality improvement and public health improvement is difficult to quantify, and the formulation of air pollution control measures requires economic or health-related data for decision making. Therefore, it is important to provide a scientific basis for formulating air pollution prevention policies.

Policies implemented to cope with climate change have co-benefits for air quality, with the air quality effects constituting a significant proportion of the overall benefits of climate policies. To alleviate the impacts of both GHGs and air pollutants on public health, the International Institute for Applied System Analysis has developed a number of tools for estimating air pollutant emissions and assessing air pollution caused by climate change or energy use, such as the Energy-Multi Criteria Analysis (ENE-MCA) Policy Tool, which provides four major modules that address costs, climate change, energy use, air pollution, health, and practicality/feasibility. The ENE-MCA tool is available to facilitate decision analysis for various types of users. The tool simulates 624 scenarios with varying combinations of climate change and energy use scenarios, as well as air pollution levels (McCollum et al., 2013).

The ENE-MCA Policy Tool primarily calculates corresponding air quality and public health benefits based on climate change and energy use scenarios. Therefore, the focus of this decision-making tool is on reducing GHG emissions under different climate change scenarios. Using this tool, calculations regarding the energy use and air pollution emissions under different climate change scenarios have been performed, while calculations regarding air quality (concentration) changes and public health exposure levels are still ongoing. Other countries also use economic or energy models to estimate the benefits of net-zero pathways in terms of GHG emissions. For example, Pan et al. (2013) used the Long-range Energy Alternatives Planning System (LEAP) model to estimate the benefits of GHG and air pollution reductions in Beijing and designed two scenarios for energy and air pollutant reductions from 2010 to 2020. The research results indicated that
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implementation of net-zero policies would have reduced Beijing's energy demand by 10 million tons of coal by 2020, and SO2 emissions reduced by 53%, NOx by 50%, PM10 by 33%, and PM2.5 by 25% (Pan et al., 2013).

Exposure to outdoor air pollution, largely caused by fuel combustion, was estimated to be responsible for approximately 2.7 million premature deaths in 2005 (GEA, 2012). Burning fossil fuels and biomass emits a large amount of air pollutants, which have a direct adverse impact on public health. In the UK, Lott et al. (2017) assessed the impact of carbon reduction strategies on air pollution using an energy model. If the UK's carbon reduction target is achieved by 2050, PM10 and PM2.5 will be reduced by 45% from 2010 to 2050, mainly owing to changes in residential heating system technology. However, pollution caused by transportation has not improved significantly. Therefore, developing environmental policies to reduce the sources of transportation pollution is necessary (Lott et al., 2017). Bridges et al. (2015) investigated the air pollution caused by coal and natural gas combustion in power plants. In the United States, power plants contribute to 70% of air pollution. The study revealed that reducing air pollution emissions from coal and gas power plants necessitates the development of relevant policies and the evaluation of the costs required. First, it is necessary to assess emissions and costs related to existing energy policies. Subsequently, simulations of air quality and assessments of costs for different energy usage policies should be conducted. Moreover, exposure levels and impacts on public health should be calculated, and social costs should be incorporated. The rationality and feasibility of energy policies can be assessed through data and the aforementioned steps (Bridges et al., 2015).

Air pollution has been a constant public health concern. Quantifying the impact of energy policies on air quality provides a scientific basis for developing effective low-carbon strategies. Nevertheless, the impact of air pollution is often overlooked in assessments of different energy usage strategies. Currently, little research has been conducted on quantifying the benefits of different energy usage strategies (e.g., modified energy mix or improved energy efficiency) and the resulting public health benefits. This study utilizes the same climate change scenario data (RCP8.5) to investigate the effects of maintaining the current energy mix versus transitioning to a decarbonized energy mix on changes in air pollution. Additionally, it examines the benefits of improved air quality on public health.

2 MATERIALS AND METHODS

The aim of the study was to estimate the correlation among low-carbon scenarios, air quality, and public health benefits in Taiwan under the same climate change scenario (RCP8.5). Using the LEAP model, the required electricity generation for 2050 was estimated and allocated to different regions. Moreover, historical emissions and electricity generation data from power plants were used to establish a relationship that considered the efficiency of pollution control devices. The equation for emissions errors was ultimately identified based on continuous adjustments. Using relevant data from the LEAP program of the Environmental Protection Administration (EPA), the emissions of each power plant in Taiwan under the reference and low-carbon scenarios for RCP8.5 in 2050 were calculated. The Weather Research and Forecasting Model (WRF) and CMAQ models were used to simulate meteorology and air quality, respectively. After obtaining the concentrations of various pollutants, BenMAP was used to estimate and monetize the public health benefits. This process successfully derived the relationship equation between electricity generation and emissions in the low-carbon scenario and obtained the co-benefit of air quality and health impact. The research framework is presented in Fig. 1.

2.1 Data Sources

The climate change data used in this study was obtained from the Coupled Model Intercomparison Project Phase 5, which can be accessed at https://pcmdi.llnl.gov/mips/cmip5/. Various climate centers around the world have provided multiple sets of climate models, called coupled general climate models, to simulate the long-term effects of different anthropogenic GHG emission scenarios, known as representative concentration pathways (RCPs), on global climate. The present study utilized the RCP8.5 scenario from the Fifth Assessment Report (AR5) for 2050.
The air quality model simulation included emission data representing Taiwan and East Asia. The East Asia emission inventory is the MIX Asia emission inventory, which includes 10 major atmospheric chemical components: SO$_2$, NO$_x$, CO, NH$_3$, NMVOC, PM$_{10}$, PM$_{2.5}$, BC, OC, and CO$_2$. The Taiwan emission data are based on the 2016 TEDS10 data and provide emission inventory for point, line, and area sources. The point source data included the latitude and longitude of each chimney, chimney height, exhaust gas temperature, emission rate, and amount of pollutant emissions. The line source provided $1 \times 1$ km grid data, showing the amount of pollutant emissions for different types of vehicles. The present study used data provided by the LEAP model of the EPA. The LEAP model assumes that the technical efficiency from 2017 to 2050 under the BAU scenario will remain at the 2016 level and considers domestic stage control objectives, international carbon-reduction technology, and regulations to design carbon-reduction simulation plans for various sectors from both technical and behavioral perspectives. Each electricity-consuming sector only calculates the GHG reduction caused by the decrease in electricity demand, and the carbon-reduction effect of the power sector is attributed to the power sector. The present study used the U.S. Federal Environmental Protection Agency's announcement of 40 CFR Part 63 Subpart UUUUU as the stricter future target for power facilities.

LEAP is an evaluation model that can analyze energy policies and climate change mitigation strategies. It allows for the setting of environment-related parameters, such as GHG emission coefficients and air pollutant emission coefficients, and can simulate the co-benefits of air pollution reduction under mitigation strategies. The LEAP model is user-friendly and enables easy acquisition of necessary data. It has been adopted by over 197 international research institutions/government agencies to simulate low-carbon development strategies, provide decision-making support for submitting UNFCCC reports, and serve as a reference for the INDC. The power sector of LEAP simulates the power generation of each power plant based on its installed capacity, power generation, and capacity factors, on the premise of meeting the electricity demand. Under the BAU scenario, the average annual growth rate of the power sector from 2015 to 2050 is 3.8%/year for the northern region, 3.3%/year for the central region, 2.8%/year for southern region 1, 0.3%/year for southern region 2, and –2.3%/year for the eastern region. The power generation structure in each region is dominated by coal-fired power plants, with the exception of the central region where gas-fired power plants have a higher share than coal-fired ones. The central region has the highest share of renewable energy, including offshore and onshore wind power and hydropower. The eastern region has the second-highest share of renewable energy, owing to its hydropower resources, whereas the northern region has the lowest share of renewable energy. The maximum carbon reduction potential of the power sector is obtained by combining all low-carbon scenarios in the industrial and other electricity demand sectors, setting a low-carbon energy target. Under
this scenario, the aggregate electricity demand in Taiwan increases from 253.6 billion kWh in 2015 to 486.9 billion kWh in 2050, with an average annual growth rate of 1.9%. The electricity demand in the northern region increases from 70.6 billion kWh in 2015 to 168.7 billion kWh in 2050, with an average annual growth rate of 2.5%. In the central region, the electricity demand increases from 69.2 billion kWh in 2015 to 186.2 billion kWh in 2050, with an average annual growth rate of 2.9%. In Southern Region 1, the electricity demand increases from 39.1 billion kWh in 2015 to 78.5 billion kWh in 2050, with an average annual growth rate of 2%. In southern region 2, the electricity demand decreases from 64.3 billion kWh in 2015 to 50.3 billion kWh in 2050, with an average annual growth rate of –0.7%. In the eastern region, the electricity demand decreases from 10.4 billion kWh in 2015 to 3.3 billion kWh in 2050, with an average annual growth rate of –3.2% (TEPA, 2019).

2.2 WRF-CMAQ Model Settings

The weather model uses the National Centers for Environmental Prediction reanalyses from the United States and four-dimensional data assimilation with grid-nudging to provide accurate meteorological simulation in the air quality model. The meteorological field for the air quality model is the WRF meteorological model, which has been widely applied in Taiwan in the past, contributing to high-resolution numerical forecasting of weather processes of different types and regions in Taiwan, and improving the resolution and accuracy of weather forecasting.

The CMAQ simulation system can simulate various chemical and physical processes that are vital for the transformation and distribution of atmospheric trace gases. The CMAQ simulation system consists of three simulation components: (1) output of the meteorological simulation system represents the description of the atmospheric state and operation; (2) emission simulation system represents the results of human and natural emissions simulation; and (3) chemical transport simulation system represents the results of chemical change simulation.

The present study simulated the entirety of Taiwan at a resolution of 3 × 3 km, with a grid size of 90 × 135. The simulation period covered four seasons, namely January, April, July, and October of the base year 2013, representing winter, spring, summer, and fall, respectively. The annual average was calculated based on the average values of these four months. As the transmission of air pollution in Taiwan has distinct regional characteristics and seasonal cycles (Yu and Chang, 2001), Taiwan is divided into seven air basins in the Taiwan-EPA data, based on terrain, wind direction, and pollution transmission conditions. As the emission sources in Taiwan are mainly concentrated on the western side, the present study compared the model performance with the monitoring values of the five major air basins in western Taiwan, presented from north to south: Northern Region, Chu-Miao, Central Region, Yun-Chia-Nan, and Kao-Ping.

To evaluate the benefits of low-carbon strategies in the power sector on air quality, we used the LEAP model to study the regional power sector and estimate the resulting impact. In terms of model performance evaluation, the quantitative results of the average Mean Fractional Bias (MFB) and Mean Fractional Error (MFE) and the correlation coefficient between simulation and observation in the base year showed values of –29%, 34%, and 0.7, respectively, which met the requirements of model simulation standards. The compliance rates for MFB, MFE, and correlation coefficient at stations within the simulation area with their standard values were 64%, 94%, respectively. Additionally, the compliance rate for the correlation coefficient above 0.5 was 99%.

2.3 Soft Combination of LEAP and CMAQ Models

In addition to simulating long-term low-carbon development strategies using the LEAP model, the present study also investigated the power sector and softly combined the CMAQ model to assess the impacts of low-carbonization in the power sector on GHG emissions and air quality.

Currently, there are two main types of thermal power plants in Taiwan: coal-fired and natural-gas-fired power plants. The calculation of air pollutant emissions for each power plant should comply with the Regulations Governing the Collection of Air Pollution Control Fee or Regulations for the Management of Reporting on Emissions of Air Pollutants from Stationary Pollution Sources in Public and Private Places, to be based on monitoring data, test results, plant-specific factors, or emission factors. In the present study, the air pollutant emissions were estimated based on
the fuel consumption calculated by the LEAP model for each power plant. The process was depicted in Fig. 2.

To estimate the future air pollutant emissions from each power plant, data on emission inventories, air pollutant emissions, fuel consumption, control measures, sulfur, and ash content were collected for the years 2010 (TEDS8), 2013 (TEDS9), and 2016 (TEDS10). The estimated air pollutant emissions in tons were calculated using the emission factor method with the collected data. To be more precise, the present study converted the entire plant emission factors into single unit factors and considered the factors of unit replacement during the calculation. However, some differences were found between the estimated pollutant emissions using the emission factor method and the emission inventories. Therefore, if the power generation unit operated normally and no unit replacement was involved, the TEDS8.1, TEDS9, and TEDS10 emission inventories were used to establish different pollutant regression formulas for each power plant unit. If unit replacement was involved, the emission factors for the new units were obtained through the electricity emission factor method, which was then used for calculation. The process workflow for future air pollutant emission estimation is presented in Fig. 3.

Direct measurement is the most reliable method for estimating air pollutant emissions. Nevertheless, owing to its high cost, it can only be conducted for a limited number of measurements, and it is typically used to focus on important, key, or special sources. Mass balance and engineering calculation methods require relevant activity and operational parameters for the input material of the emission source to accurately calculate emissions. The most convenient and commonly used method is to use emission factors for estimation. The basic formula for estimating emissions using emission factors is as follows:

\[ \text{Emissions} = \text{Emission coefficient} \times \text{activity level} \times \text{control factor}. \]

The estimation of pollutant emissions using the emission factor method has relied on three key pieces of data: emission factor, activity level, and control factor.

The selection of the emission factor is typically based on a few actual measurement-based emission factors, whereas most are referenced from the "Compilation of Air Pollution Emission Factors" (AP-42), published by the U.S. Environmental Protection Agency. The activity level and control factor are obtained from the latest emission inventories (TEDS).

In the present study, the emission factor method was used to calculate pollutant emissions, and the TEDS 8.1, TEDS 9.0, and TEDS 10.0 emission inventories were estimated to meet the needs of air quality control and modeling users to enable detailed analysis of emission temporal characteristics. Finally, CMAQ modeling was performed.

Fig. 2. Diagram of LEAP and CMAQ data links.
2.4 Air Pollution and Public Health Benefits Analysis

BenMAP has been developed in the United States as an air pollution health impact assessment system, and as of now, it has not yet been directly introduced for use in other countries. Owing to its customization flexibility and ease of operation, the system is widely used in the United States for evaluating control strategies for various federal and state air quality issues, such as PM$_{2.5}$, O$_3$, power generation, and transportation pollution sources (Ostro and Chestnut, 1998; Davidson et al., 2007; Fann et al., 2012). Additionally, many countries such as Spain and South Korea have adopted the system for health impact assessments through combination with databases specific to their country or region (Bae and Park, 2009; Boldo et al., 2011). Australian scholars used the BenMAP system to evaluate the health benefits obtained from improving air quality. Evaluation results showed that reducing PM$_{2.5}$ exposure by 10% in Sydney, Australia, in 2007 could reduce premature deaths by approximately 650 people and hospitalizations owing to respiratory and cardiovascular diseases by 700 people in 10 years (Broome et al., 2015). Thompson et al. (2014) used CMAx and BenMAP to evaluate the co-benefits of US carbon policies, and the study found that the health benefits from improved air quality could offset the costs of carbon reduction policies by 26%–1050%. Observably, the BenMAP system can evaluate the health and cost benefits of air pollution control, providing decision-makers with a sound basis for constructing environmental policies. It can be flexible according to the scale of analysis required by researchers or policy-makers, ranging from cities, regions, and countries to the global level. Along with monitoring data, various air quality model simulation results can be integrated into the analysis interface of the system.

The present study established a BenMAP system database, the database settings of which are presented in Table 1.

3 RESULTS AND DISCUSSION

In assessing the impact of low-carbon strategies on air quality, climate change was also found to be a key factor affecting air pollution. In the evaluation of long-term carbon reduction strategies
Table 1. BenMAP database.

<table>
<thead>
<tr>
<th>Type of database</th>
<th>Data in 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data of geographic domains</td>
<td>Domains of villages, towns, counties and cities in Taiwan and $3 \times 3$ km grid</td>
</tr>
<tr>
<td>Pollutant monitoring data</td>
<td>PM$_{2.5}$ monitoring data across Taiwan in 2016</td>
</tr>
<tr>
<td>Data of incidence rate, prevalence rate and death rate of diseases</td>
<td>✓ All-cause (2016)</td>
</tr>
<tr>
<td></td>
<td>✓ Cardiovascular diseases (2016)</td>
</tr>
<tr>
<td></td>
<td>✓ Respiratory diseases (2016)</td>
</tr>
<tr>
<td>Death rate</td>
<td>✓ All-cause (2016)</td>
</tr>
<tr>
<td></td>
<td>✓ Cardiovascular diseases (2016)</td>
</tr>
<tr>
<td></td>
<td>✓ Respiratory diseases (2016)</td>
</tr>
<tr>
<td>Admission rate</td>
<td>✓ Cardiovascular diseases (2016)</td>
</tr>
<tr>
<td></td>
<td>✓ Respiratory diseases (2016)</td>
</tr>
<tr>
<td>Population data</td>
<td>Import of actual population in the all-age minimum statistical area in 2016</td>
</tr>
<tr>
<td>Health impact function (CR-Functions)</td>
<td>Meta-analysis was implemented to health impact function of the same type of health evaluation item by using random effect approach, respectively (pooling; meta-analysis).</td>
</tr>
<tr>
<td>Literature of health impact function: Beelen et al. (2014); Cesaroni et al. (2013); Crouse et al. (2012); Jerrett et al. (2013); Lepeule et al. (2012); Pope III et al. (2002)</td>
<td></td>
</tr>
</tbody>
</table>

using CMAQ, the chemical transport mechanism was calculated based on input meteorological data. The climate scenario used in this case was the 2050 AR5 RCP8.5, with a dynamic downscaling resolution of $3 \times 3$ km. According to projections of future climate trends in Taiwan, the number of days with temperatures above 36°C will increase. In the worst-case scenario (SSP5-8.5), the increase will be 8.5–48.1 days in the middle to the end of the 21st century. Urban areas will experience a more significant increase in temperature than other regions. In the ideal mitigation scenario (SSP1-2.6), the increase will be 6.6–6.8 days. It is estimated that the length of the summer season in Taiwan will increase from the current 130 days to 155–210 days in the future, whereas the length of the winter season will decrease from the current 70 days to 0–50 days. The changes will be substantial under the worst-case scenario but relatively moderate under the ideal mitigation scenario (IPCC, 2021).

3.1 Methodology for Estimating Air Pollutant Emissions from Power Plants under climate Change Scenarios

In the present study, the amount of air pollutant emissions were estimated to predict future emissions under a low-carbon scenario. To enhance the realism of the estimated emissions, we employed regression formulas based on TEDS 8.1, TEDS 9, and TEDS 10 to adjust the emissions. In this study, Taiwan was divided into the Northern Region, Central Region, Yun-Chia-Nan, and Kao-Ping regions, with emissions from power plants in each region being estimated. Under the BAU scenario, the TSP, PM$_{2.5}$, SO$_x$, and NO$_x$ emissions from power plants in the north were 1058.9, 724.2, 15,227.6, and 13,866.2 tons year$^{-1}$, respectively. In the central region, the TSP, PM$_{2.5}$, SO$_x$, and NO$_x$ emissions from power plants were 1798.3, 969.9, 15,182.1, and 26,570.2 tons year$^{-1}$, respectively. In the Kaohsiung-Pingtung region, the TSP, PM$_{2.5}$, SO$_x$, and NO$_x$ emissions from power plants were 849.1, 505.9, 10,079.5, and 13,986.1 tons year$^{-1}$, respectively. Under the maximum carbon reduction scenario, the TSP, PM$_{2.5}$, SO$_x$, and NO$_x$ emissions from power plants in the north were 1153.8, 690.3, 15,182.1, and 26,570.2 tons year$^{-1}$, respectively. The TSP, PM$_{2.5}$, SO$_x$, and NO$_x$ emissions from power plants in the central region were 719.0, 530.5, 1282.4, and 13,629.8 tons year$^{-1}$, respectively. In the Kaohsiung-Pingtung region, TSP, PM$_{2.5}$, SO$_x$, and NO$_x$ emissions from power plants were 340.4, 273.2, 1,003.2, and 6,170.5 tons year$^{-1}$, respectively. From the perspective of the BAU and maximum carbon-reduction scenarios, the reduction of SO$_x$ and NO$_x$ were the highest, with a reduction rate of 90–95% for SO$_x$ emissions and 13–56% for NO$_x$ emissions nationwide. The detailed formulas are provided in the attached document for supplement.
3.2 Assessment of Air Quality Improvements in the Power Sector

The present study first applied the 2050 meteorological field provided by National Center for Atmospheric Research to simulate the WRF meteorological model. Subsequently, the LEAP model was used to estimate the emissions of air pollutants from the power sector in both the BAU and low-carbon scenarios. Finally, the CMAQ model was used to simulate the air quality benefits under both scenarios.

The present study simulated two scenarios for the year 2050, the BAU and carbon-reduction scenarios, in which only emissions from the power sector were reduced, while emissions from other sectors remained unchanged. Fig. 4 shows the air quality benefits of the CMAQ model simulation for PM$_{2.5}$ in 2050. The annual average concentration of PM$_{2.5}$ in Taiwan was 17.7 µg m$^{-3}$ in the BAU scenario, whereas the concentration in the carbon reduction scenario for the power sector was 17.0 µg m$^{-3}$. If the power sector implements carbon reduction measures, the annual average concentration of PM$_{2.5}$ in Taiwan would decrease by 0.7 µg m$^{-3}$ or approximately 4%. The PM$_{2.5}$ concentration difference map shows that the reduction effect in the central and southern regions is significant. Zapata et al. (2013) analyzed the air quality impacts of California Assembly Bill 32 (Global Warming Solutions Act of 2006; AB 32), which proposed to substantially reduce GHG emissions from all economic sectors by 2020 through energy efficiency, renewable energy, and other technological measures. Most AB 32 scope-defined planning measures would simultaneously reduce emissions of both conventional pollutants and GHGs, thereby improving air quality in California. The study indicated that the implementation of AB 32 measures would result in reductions of 1% and 15% for PM$_{2.5}$ and NO$_x$, respectively. These reductions would lead to a 6% decrease in population-weighted PM$_{2.5}$ concentrations in California, reducing the state’s air pollution mortality rate by 6.2%. Under 2030 conditions, the measures could prevent 880 (560–1100) premature deaths per year. Although the present study only investigated the power sector, the obtained results and those from Zapata et al. (2013) indicated that energy efficiency improvements can help reduce PM$_{2.5}$ concentrations, particularly for cities with substantial industrial (point source) emissions.

Fig. 5 presents the O$_3$ concentrations simulated by the CMAQ model in 2050 under the BAU and power sector carbon-reduction scenarios. The simulated concentrations are 29.9 ppb (Fig. 5(a)) and 30.2 ppb (Fig. 5(b)), respectively, representing an increase of approximately 0.3 ppb. Fig. 5(c) represents the difference between the BAU scenario and the low carbon scenario. The rise in
Fig. 5. O₃ annual concentration in difference scenarios in 2050. (unit: ppb)

Ozone levels is attributed to the utilization of the RCP8.5 scenario in the BAU projection for 2050, compounded by the energy policy’s transition from coal-fired power plants to natural gas-fired ones, resulting in an increase in O₃ levels instead of a decrease. Negative values in Fig. 5(c) denote a decline in concentration. Hence, deeper shades of blue indicate regions where the reduction in PM₂.₅ concentration is more pronounced. Thompson et al. (2014) also found that under climate policies and the BAU scenario for 2030, the overall average concentrations of both O₃ and PM₂.₅ decrease; however, in urban areas or regions with higher NOₓ emissions, O₃ concentrations may increase instead.

### 3.3 Health Benefits

The present study investigated the health benefits of the BAU and low-carbon scenarios in the power sector in 2050. The BenMAP system primarily used all-cause mortality as the evaluation basis, with the number of avoidable deaths as the long-term health impact indicator and the number of avoidable hospitalizations owing to cardiovascular disease and number of avoidable hospitalizations owing to respiratory disease as short-term health impact indicators. The statistical value of a life was used to estimate the monetized value of the long-term health benefits that can be obtained from air quality improvement. The cost of illness was used to estimate the monetized value that can be obtained, which represents the short-term health benefits. The results of the evaluation showed that, with implementation of carbon reduction measures by the power sector, air quality improvement can prevent 1012 (374–2463) deaths nationwide, with a health monetization value of approximately 48.9 billion Taiwanese Dollars (TWD); short-term health benefits can prevent 45 (13–76) and 53 (0–141) hospitalizations from cardiovascular disease and respiratory disease, respectively, with monetization values of approximately 5.10 million and 4.44 million TWD, respectively. Fig. 6 indicates the regional distribution of the number of avoidable deaths and hospitalizations and the monetization values of air quality improvements. In the low-carbon scenario, urban areas exhibit higher numbers of avoided deaths and hospitalizations. Overall, due to the reduction in PM₂.₅ concentrations and factors such as dense urban populations, Taipei, Taichung, and Kaohsiung regions experience better public health benefits. It was found that the areas with higher health impact levels in Fig. 6(a) and the PM₂.₅ delta concentration variation map in Fig. 4 are similar to the results of Zapata et al. (2013). Moreover, it was revealed that the implementation of low-carbon strategies would lead to greater improvement in air quality and
Fig. 6. (a) Number of attributable to death avoided, (b) inpatients of cardiovascular diseases avoided, and (c) inpatients of respiratory diseases avoided.

Table 2. Assessment of health benefits in the carbon-reduction scenario.

<table>
<thead>
<tr>
<th>Health Endpoint</th>
<th>Health Events Avoided (95% CI)</th>
<th>Mean Valuation (million TWD) (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$-related mortality</td>
<td>1,012 (374–2,463)</td>
<td>132,461.42 (48,900.43–322,249.98)</td>
</tr>
<tr>
<td>PM$_{2.5}$-related cardiovascular hospitalizations</td>
<td>45 (13–76)</td>
<td>5.1 (1.51–8.68)</td>
</tr>
<tr>
<td>PM$_{2.5}$-related respiratory hospitalizations</td>
<td>53 (0–141)</td>
<td>4.44 (0–11.81)</td>
</tr>
</tbody>
</table>

consequent health benefits in urban areas with a large number of point sources than in other regions. The detailed data is presented in Table 2.

4 CONCLUSIONS AND RECOMMENDATIONS

The present study evaluates the GHG reduction and air quality improvement benefits of low-carbon measures in the power sector by combining the LEAP and CMAQ models. We used emission inventories from 2010 (TED8.1), 2013 (TEDS9), and 2016 (TEDS10) to establish regression formulas for future emissions of power generation units. These formulas were used to estimate emission coefficients for different fuels used in each power plant. When calculating emissions from the low-carbon scenario in the electricity sector, this research utilize the RCP8.5 climate scenario data to investigate the effects of decarbonization on air pollution and public health.

The emission coefficients were then input into the LEAP model to simulate the air pollutant emissions under both the BAU and carbon-reduction scenarios in the power sector, and the CMAQ system was employed to evaluate the air quality benefits under the two scenarios in the year 2050. The simulation results show that the carbon reduction measures in the power sector can improve air quality by 2050, with an estimated average annual reduction of 0.7 $\mu g m^{-3}$ (4%) in PM$_{2.5}$, an increase of 0.3 ppb (1%) in O$_3$, a decrease of 0.07 ppb (12%) in SO$_x$, and a decrease of 0.11 ppb (4.2%) in NO$_x$. The findings of this study indicate that Taiwan is a mixed region characterized by a combination of industrial, residential, and transportation activities. If only the power sector is targeted for emission reduction, the areas most affected will be Taipei, Taichung, and Kaohsiung. Incorporating other low-carbon strategies, such as low-carbon transportation, is recommended
to achieve a triple-win situation of low carbon, improvement in air quality, and public health benefits.

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SUPPLEMENTARY MATERIAL

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