Energy Policy 88 (2016) 278–288

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Impact of a national plan for future electricity supply on ambient air quality in South Korea

Changsub Shim*, Jiyoun Hong

Korea Environment Institute, 370 Sicheong-daro, Sejong, South Korea

HIGHLIGHTS

- Air quality impact assessment of future electricity supply plan was conducted.
- Future emissions changes by expansion of electricity capacity was estimated.
- Future coal-powered plants can cause intense NO_x emissions over Seoul, Korea.
- Consequent NO_2 level will increase significantly over Seoul Metropolitan Area.

ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form
22 October 2015
Accepted 24 October 2015

Keywords:
Air pollutant emission
Air quality
Coal
Electricity power generation
Seoul metropolitan area

ABSTRACT

South Korea has recently chosen coal as the major energy source for the future national electricity power supply, mainly due to economic reasons. This has raised concerns about national air quality, considering the serious air pollution associated with the long-range transport of Chinese air pollutants. In the present study, we simulated air pollution levels for 2027 considering the changes in electricity power plants of South Korea proposed by the sixth Basic Plan for Long-Term Electricity Supply and Demand (6th BPE, 2013–2027). Compared to the emissions in 2010, the emissions of CO, NO_x, SO_x, and PM_{10} from electricity supply in the Incheon, Gyunggi, Gangwon, Chungnam, and Gyeongnam regions will increase by 20–50% in 2027. The resulting number of days on which pollution levels exceeded the national air quality standards for O_3 and PM_{10} will increase by fewer than 6 days in all regions, which seems to be a minor increase. However, that of NO_2 over the Seoul metropolitan area (SMA, including Incheon, part of Gyunggi, and Seoul) showed a marked increase of more than 21 days. Therefore, an impact from secondary air pollution, such as acid rain and $PM_{2.5}$ formation, can be expected, although this requires quantification.

1. Introduction

Air pollution in the Seoul metropolitan area (SMA) of South Korea is more severe than in metropolitan cities of other continents based on the concentration of air pollutants such as nitrogen oxides (NO_x) and particulate matter (PM) (Organization for Economic Co-operation and Development (OECD), 2008)). The introduction of emissions reduction technologies and the use of clean energy have reduced some primary air pollutants such as CO and SO_2 for the past 10 years (Korean Ministry of Environment (KMOE), (2012)). However, despite such efforts, a continuous increase in the number of motor vehicles and industrial facilities is interrupting significant mitigation of NO_x and PM_{10} as well as ozone (O_3) in Korea (KMOE, 2012). In particular, the annual mean $PM_{2.5}$ concentration over most Korean cites has recently exceeded 25 μg/m^3, which is much higher than that recommended by the guideline of the World Health Organization (WHO, 10 μg/m^3) (Interagency of the Korean government, 2013).

The electricity consumption of South Korea has increased rapidly over the past 10 years. In 2011, total domestic electricity consumption was about 450,000 GW h, which was about a 61% increase compared to that of 2002 (280,000 GW h). This consumption ranks in the top eight of the world (Korean Ministry of Knowledge & Economy (KMKE), 2013). Korean electricity consumption is also relevant to national greenhouse gas emissions. Currently, Korea is ranked seventh in CO_2 emissions (Le Quéré et al., 2014).

Korea has built new power plants that use coal, nuclear power, and natural gas (i.e., liquefied natural gas [LNG]) to meet the

---

* Corresponding author. Fax: +82 44 415 7866.
E-mail address: marchell@gmail.com (C. Shim).

http://dx.doi.org/10.1016/j.enpol.2015.10.033

increasing demand. In particular, electrical power generation using coal and LNG has dramatically increased. The share of electricity generation by fossil fuels (mostly coal and LNG) in terms of final energy increased from 51% in 2002 to 64% in 2012 (KMKE, 2013). This trend could worsen domestic air quality despite various mitigation policies that have been put in place.

In February 2013, the Korean government announced the sixth Basic Plan for Long-Term Electricity Supply and Demand (6th BPE, 2013–2027), which is a biennial plan to guide national electricity policy based on long-term predictions of electrical supply and demand associated with the projection of the national economy (KMKE, 2013). According to this plan, South Korean electricity consumption is expected to increase to 770,000 GW h in 2027, which is an increase of more than 60% compared to 2012. Moreover, coal and LNG will provide a major portion of the energy sources for the electrical supply. Therefore, it is necessary to quantitatively assess the future impact of air pollutant emissions on domestic air quality.

According to the Second National Energy Master Plan of South Korea, a higher-level plan of the BPE announced in January 2014, total final energy consumption in the country is expected to increase about 21% by 2035 (254.1 MToe [million tonnes of oil equivalent]) compared to 2011 (205.9 MToe). In particular, the final energy consumption by electricity is expected to rapidly increase by 80% (Private–Public Working Group of Korean Ministry of Trade, Industry & Energy (MOTIE), 2014). Intense dependency on electricity generated from fossil fuels can cause an increase in air pollutant emissions from combustion in energy industry sector.

In the present study, we assessed the potential impact of the aforementioned electricity supply plan on ambient air quality in the SMA, which has a population of nearly 20 million. Considering the impact of future increases in the number of national electrical power facilities, we have discussed the energy and environmental policies of South Korea. In particular, we quantitatively analyzed the plan's potential impact on future changes in O_3, O_3 precursors (e.g., NO_x), and PM_{10} (PM less than 10 μm in diameter), which influence human health. We estimated the changes in 2027, the final year of the sixth BPE. The remainder of this paper is organized as follows. The methodology is described in Section 2, and Section 3 reports the results of air-quality model simulations.

2. Data and methodology

2.1. Sixth BPE (2013–2027)

The Korean Ministry of Trade, Industry, and Energy (KMOTIE, previously Korean Ministry of Knowledge & Economy [KMKE]) establishes a 15-year action plan every 2 years (Korea Electricity Business Act Enforcement Ordinance Article 15) aimed at developing a stable national power supply (Korea Electricity Business Act Article 25). In February 2013, the KMKE officially announced the sixth BPE (2013–2027) and reported demand management goals, proper reserve rates, power mixes, proportions of renewable energy, and power plant construction plans until 2027 (KMKE, 2013; Lee et al., 2015a). According to the plan, Korea's electricity demand is expected to increase ~4% annually, reaching 770,000 GW h in 2027, which is about a 60% increase compared to 2012.

As shown in Fig. 1, future energy sources of the electrical power supply are expected to include a higher proportion of renewable energy (12.6%) in 2027 compared to the current level. Although dependency of fossil fuels (including coal and LNG) for electricity generation in terms of final energy will slightly decrease from 60% in 2012 to 50% in 2027, total fossil fuel consumption for electrical generation in terms of primary energy is expected to increase rapidly by 58% in 2027 compared to 2012. This is because the total electrical consumption is expected to significantly increase (KMKE, 2013), despite the government's effort to reduce the emissions of greenhouse gases.

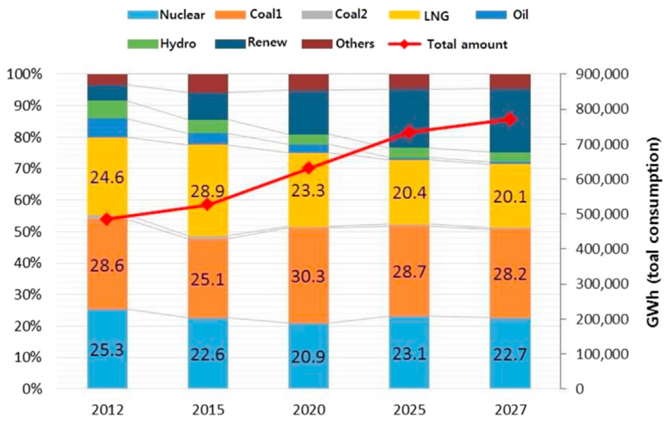

Fig. 1. Projections of future national electricity consumptions (unit at the right axis) and the power mix for electricity generation (unit at the left axis) according to the sixth National Plan for Electricity Supply (BPE) of Korea. (sources: KMKE, 2013). "Coal2" denotes anthracite coal. "Renew" denotes the renewable energy excluding hydro energy.

To satisfy future demand for electricity, the Korean government has planned to install 18 additional electrical power plants by 2027 (totaling 15.8 million kW). Six facilities by four public enterprises (4.04 million kW) and twelve facilities by eight private power generation companies (11.76 million kW) will be installed by 2027.

2.2. National emissions of air pollutants

The National Institute of Environmental Research (NIER) of Korea has operated the Clean Air Policy Support System (CAPSS), which has calculated the emissions of air pollutants since 1999. It estimates air pollutants such as CO, NO_x, SO_x, PM_{10}, and volatile organic compounds (VOCs). According to CAPSS data for the year 2010, South Korean emission of NO_x exceeded 1 million tonnes (Table 1), which made it the largest pollutant emission. Although NO_x emissions have decreased continuously since the year 2000, the rate of decrease has not been sufficient, mainly due to the rapidly increasing number of motor vehicles. The second largest pollutant emission was VOC (860,000 tonnes), followed by CO (766,000 tonnes).

Fig. 2 shows the emissions sources for each pollutant. NO_x and CO, which can be relevant to the formation of O_3, are mainly

Table 1
Korean air pollutant emissions by major sources classification in 2010 (sources: NIER, 2012) (unit: tonne).

Sources	CO	NO_x	SO_x	PM_{10}
Combustion in energy industry (electricity supply)	46,679	138,355	70,923	2,695
Combustions in energy industry (heat supply)	3850	15,086	10,657	121
Non-industrial combustion plants	83,435	96,480	57,810	2421
Combustion in manufacturing industries	17,706	164,942	103,733	76,011
Production processes	19,719	49,022	93,365	6451
Road transport	520,386	382,226	798	15,255
Other mobile sources and machinery	66,793	208,878	62,919	13,401
Waste treatment and disposal	955	6062	1528	165
Other sources & sinks	6645	158	0	288
Total	766,268	1,061,209	401,742	116,808

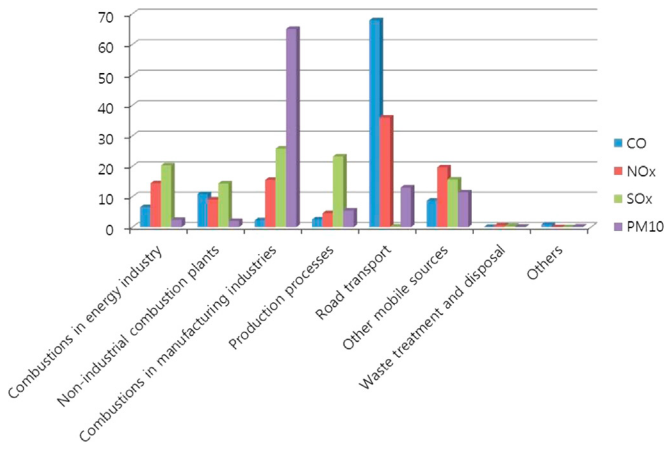

Fig. 2. The contribution ratio (%) of air pollutant emissions by major emission sources (based on major classification) (sources: NIER, 2012).

emitted by vehicle combustion (accounting for 68% and 36% of totals, respectively). Manufacturing combustion accounts for the largest portion (65%) of PM_{10} emissions, an important index of the health impact (Fig. 2). Combustion in energy industry (majority is electricity supply) is associated with 20% of SO_x emissions, 14% of NO_x, 7% of CO_x, and 2% of PM_{10}. These data indicate that relatively fine particles (PM_{10}) are not significantly emitted from combustion in energy industry (NIER, 2012). Oil power generation is currently responsible for only 9% (4890 MW) of total electricity generation in fossil fuel-based power stations, and this figure will decrease to less than 2% (1249 MW) by 2027 according to BPE. Thus, we do not discuss the impact of oil power generation in the present study. However, the sixth BPE calls for increasing coal- and LNG-based power facilities by 1.9 and 1.3 times, respectively. That implies that fossil fuel-driven power generation will likely continue to be the major emission source from the Korean electricity supply industry.

2.3. GEOS-Chem simulation

We used GEOS-Chem, an atmospheric chemical transport model, to evaluate the impact of the BPE on the ambient air quality in Korea. GEOS-Chem is a Eulerian model with NASA's assimilated meteorological field (GEOS-5), which has the capability to calculate three-dimensional information about ~70 chemical compounds (http://wiki.seas.harvard.edu/geos-chem/index.php). Its horizontal resolution for nested simulation is $0.5° \times 0.667°$ over the Asian domain; it uses the lateral boundary condition of chemical fields at a global scale resolution ($2° \times 2.5°$) (Chen et al., 2009). For modeling, we applied the emissions inventory of Zhang et al. (2009) and Streets et al. (2006), which was estimated through the Intercontinental Chemical Transport Experiment Phase B (INTEX-B) project for the Asian region (Streets inventory). Streets inventory is based on cooperative research between the US and China: it estimated East Asian air pollutants by inversely estimating the long-range transport of air pollutants, focusing on aircraft observations and satellite data in the troposphere (Zhang et al., 2012; Na et al., 2013). This inventory constructed the emissions of eight pollutants (SO_2, NO_x, CO, $PM_{2.5}$, PM_{10}, NMVOC, BC, and OC) at a spatial resolution of $0.5° \times 0.5°$; the region encompasses East Asian countries including Korea, China, and Japan (Fig. 3). The amount of air pollutants was estimated for anthropogenic emissions sources including four sectors (power, industry, residential, and transportation), and natural emissions, such as biomass burning and biofuel burning (Zhang et al., 2009). We used Streets inventory as a baseline simulation for the entire domain (Fig. 4) to evaluate the model performance, because the GEOS-Chem with CAPSS emissions results in greater underestimation of CO and PM_{10} over Korea (not shown). To reflect emissions changes resulting from the BPE, we modified the Streets inventory over the South Korea region for 2027, applying the ratio of CAPSS emissions between 2027 (6th BPE) and 2010.

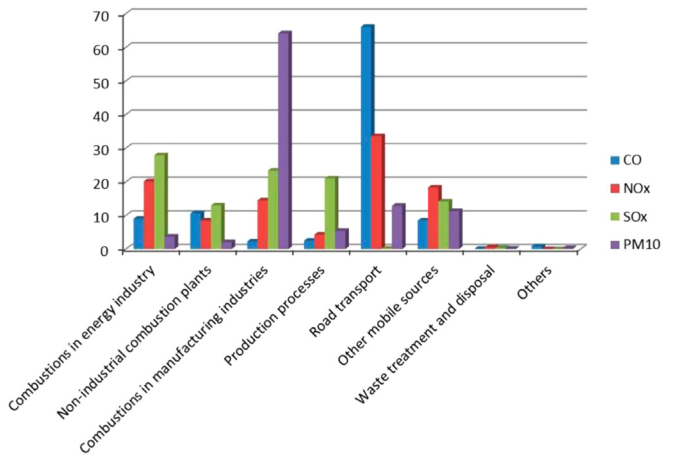

Fig. 3. The same as Fig. 2, but for year 2027, applying 6th BPE to the emissions inventory of electricity supply which is a sub-sector of the combustions in energy industry. We assume the emissions amounts for the rest of the sectors are same as year 2010.

2.4. Evaluation of model performance

The results of numerical analysis need to be verified by observations to discuss the environmental impact of national electricity policy on a scientific basis; we evaluated our GEOS-Chem simulations by comparing them to ground observations for the year 2009 as GEOS-Chem emissions inventory for East Asia was available up to 2009 (http://wiki.seas.harvard.edu/geos-chem/index.php/Scale_factors_for_anthropogenic_emissions). The corresponding domestic ground observation data (within the model's spatial resolution of $\sim 50 \times 60$ km^2) were collected and compared. Air-quality analyses were conducted for four regions of Korea where higher emissions are expected based on the sixth BPE and the potential exposure of large populations near or within the SMA to the consequent air quality (western SMA, eastern SMA, Chungnam, and Gangwon) (Fig. 4). The impacts of potential meteorological changes associated with future climate change were not considered because we used the same assimilated meteorology of GEOS-5 for 2009 and 2027.

The KMOE and local governments installed 11 types of measurement networks and continuously collected data; the networks were installed and managed at 477 locations in 97 cities of South Korea (NIER, 2013). Measured data from each station were sent to the National Ambient Air Monitoring System (NAMIS) and the data went through a statistical process to produce the final data for the National Institute of Environmental Research (NIER) (NIER, 2013). Air pollutants such as SO_2 and CO were measured using official test methods according to the Environmental Policy Act of Korea. SO_2 was measured using the pulsed UV fluorescence method, CO via the non-dispersive infrared method, NO_2 using chemiluminescence analyses, O_3 through UV photometry, and PM_{10} via β-ray absorption (NIER, 2013). The number of ground stations sampled for the four corresponding GEOS-Chem grids representing selected regions (Fig. 4) was 42 for western SMA, 21 for eastern SMA, 5 for Chungnam, and 3 for Gangwon.

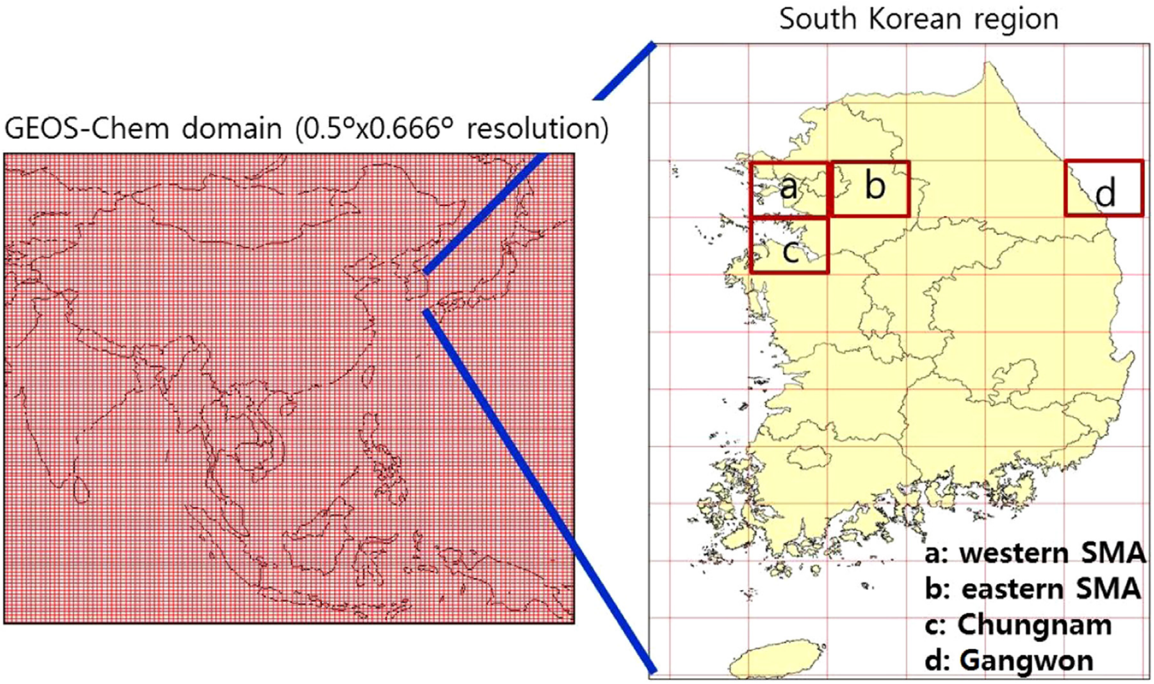

Fig. 4. The model domain for nested simulation over south east Asia (left) and the selected local grid to assess the impact of the sixth BPE on air quality of South Korea (right). The four local area (red boxes from a to d; western and eastern Seoul Metropolitan Area (SMA), Chungnam, and Gangwon) are defined. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Estimation of pollutant emissions by the sixth BPE

The future national emissions in 2027 due solely to the sixth BPE can be estimated by applying the changes in energy mixes and electrical power generation capacity to current emissions from electricity supply industry in the CAPSS emissions inventory. In terms of the major pollutants emissions from combustion in energy industry, our calculations showed that the BPE will result in an approximately 50% increase by 2027. In particular, emissions of CO, NO_x, SO_x, and PM_{10} from combustion in coal power plants will increase the most (by 1.4, 1.5, 1.52, and 1.56 times, respectively, Table 2 and Fig. 3). Regarding national total emissions (including all emission sectors), SO_x and NO_x are expected to increase 1.13 times and 1.08 times, respectively by the BPE. CO, PM_{10}, and VOC are expected to change less than 3%, 2%, and 1%, respectively (Table 2). The national total amount of all air pollutant emissions is estimated to increase by about 5% due to the 6th BPE.

3.1.1. Changes in local government emissions

To project changes in the regional distribution of emissions, we estimated the electrical power capacity of each local government in 2027, using the Electric Power Statistics Information System (EPSIS, https://epsis.kpx.or.kr) for 2010. The average emissions from major fuels (i.e., coal, oil, LNG) per installed capacity was calculated based on 2010 CAPSS data. Estimations of spatial changes in future emissions can be applied to a global chemical transport model to assess the impact of air quality, which is described in the next section. Figs. 5 and 6 show the status and spatial changes in the installed capacity of power plants of South Korea for coal and LNG. The left side of each figure shows the regional distribution of current power plants (coal and LNG), whereas the right side shows the projection in power plants expected by 2027. Table 3 compares the electricity generation capacity of local government between 2010 and 2027. The results indicate that the Chungnam region will have the largest generation capacity of 24,863 MW (~30%) by 2027. According to the BPE, power plant expansion will occur in Gangwon, Chungnam, Incheon, and Gyunggi by 2027 (Table 3 and Figs. 5 and 6).

Table 2
The emissions ratio between 2027 and 2010 for combustions in energy industry and national total emissions solely by the sixth BPE.

2027/2010	CO	NO_x	SO_x	PM_{10}	VOC
Only for combustions in energy industry	1.4	1.5	1.52	1.56	1.35
Total national emissions	1.03	1.08	1.13	1.02	1.00

To calculate regional changes in pollutant emissions (CO, NO_x, SO_x, and PM_{10}) in the year 2027, we devised emissions factors for each region based on the emissions per unit generation capacity (see above) in terms of emissions (kg) per unit generation capacity (kg/MW). Because emissions factors vary widely by region and individual power plants, each of which has different equipment and facilities, we used the median value of all emissions factors as the national emissions factor for each fuel. Table 4 presents the results. The emissions factor for coal was the highest because it included the values for NO_x and SO_x (4961 and 1657 kg/MW, respectively: Table 4).

According to the estimation, changes in regional emissions by the sixth BPE will proceed as follows. Gangwon plans to construct coal power plants in the cities of Samcheok and Donghae (on the eastern coast of the Gangwon region) by 2027. This area will thus account for about 9000 MW of additional electricity supply compared to 2010, and annual emissions of CO, NO_x, SO_x, and PM_{10} will increase by 8000, 45,000, 27,000, and 1300 tonnes, respectively. This is akin to increases of 27% for CO emissions, 47% for NO_x, 50% for SO_x, and 2% for PM_{10} over 2010 values. Because the Gangwon region already emits the largest amount of PM_{10} from industries such as cement production, the increase of 1300 tonnes of PM_{10} does not significantly increase the emissions ratio. For Incheon, one of the large cities located west of the SMA, the main new plants will be coal power plants on Yeongheung Island. Although

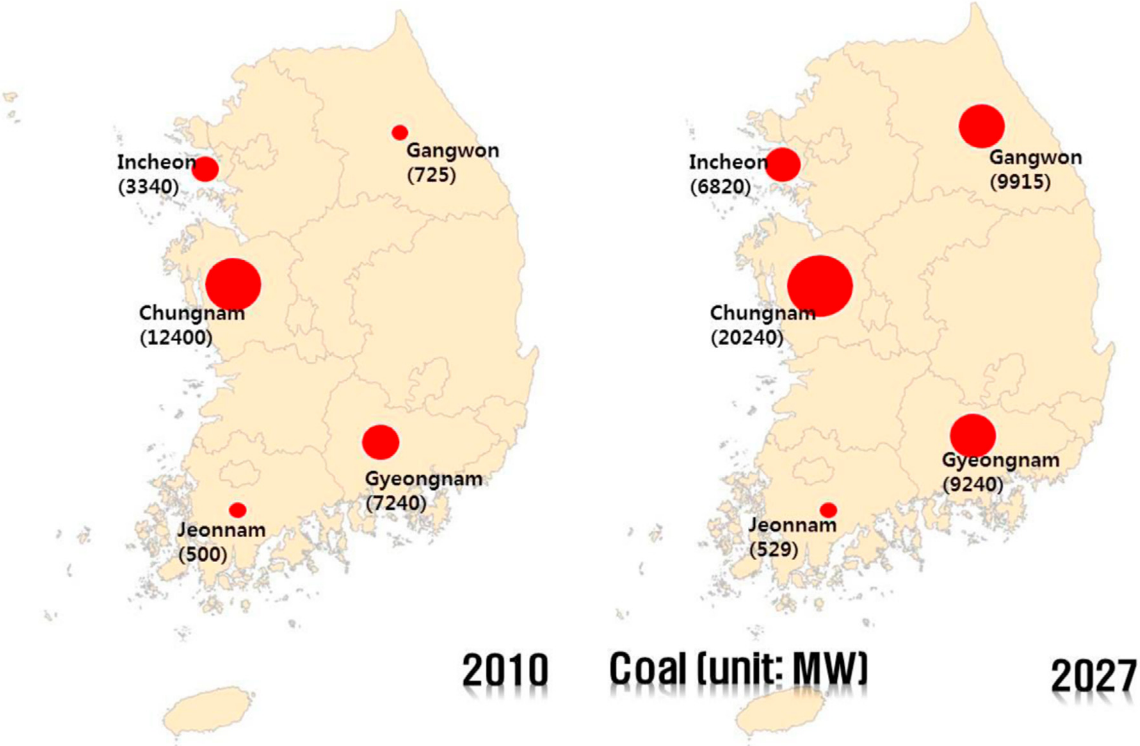

Fig. 5. The regional changes of installed capacity of power plants of South Korea for coal power plants. The left side of each figure shows regional distribution of current power plants in 2010, while the right side shows the projection of power plants by the sixth BPE in 2027. (Unit: MW).

this will lead to an increase in the power supply of about 3500 MW compared to 2010, there will also be an estimated decrease of 2000 MW in this area due to partial retirement of an LNG power plant (Table 3). The annual emissions increases will be 270, 14,000, 10,000, and 440 tonnes for CO, NO_x, SO_x, and PM_{10}, respectively. The increased NO_x and SO_x emissions could have a possible influence on the air quality of the SMA. Compared to the emissions in Incheon in 2010, the increase of CO emissions in 2027 will be similar, whereas NO_x, SO_x, and PM_{10} will increase by 30%, 57%, and 17%, respectively.

Due to concerns of exposing the largest population center in the country to emissions, no additional coal power plants are

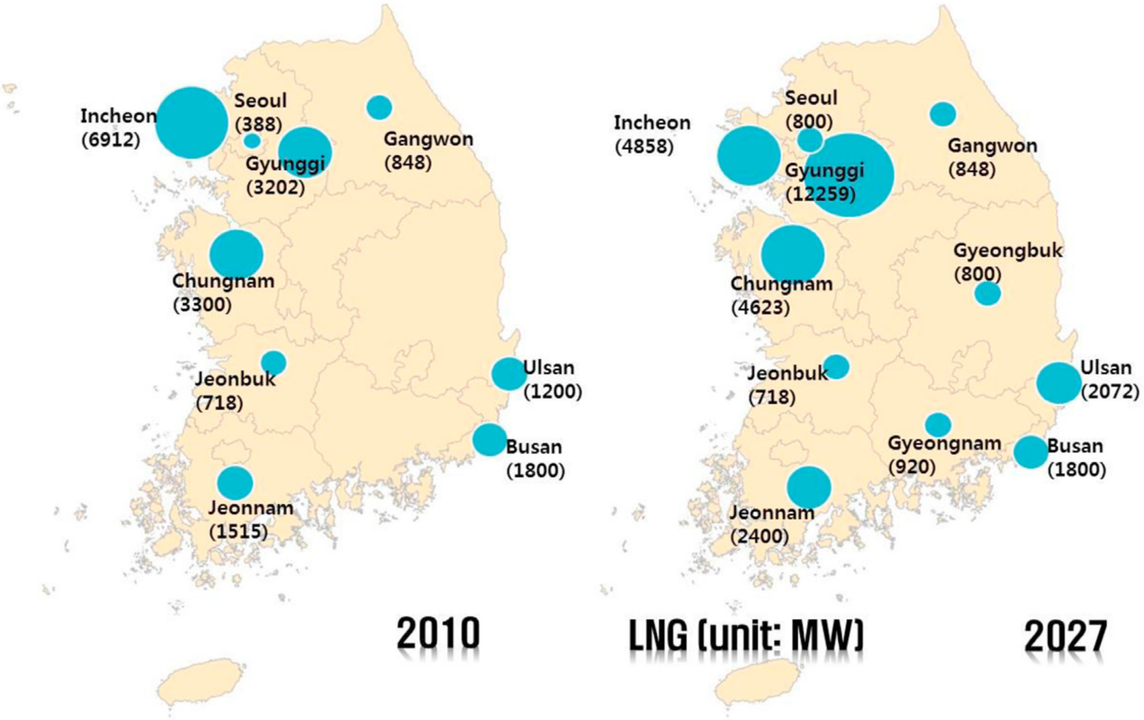

Fig. 6. The same as Fig. 5, but for LNG power plants.

Table 3
The comparison of electricity generation capacity by local government of South Korea between 2010 (left) and 2027 (right) based on the sixth BPE.[a]

(Unit: MW)

Local government	2010			2027		
	Coal	Oil	LNG	Coal	Oil	LNG
Seoul	–	–	387.5	–	–	800.0
Busan	–	–	1800.0	–	–	1800.0
Incheon	3340.0	–	6912.4	6820.0	–	4858.4
Ulsan	–	2200.0	1200.0	–	Retired	2072.0
Gyunggi	–	1400.0	3202.1	–	Retired	12,259.1
Gangwon	725.0	–	848.0	9915.0	–	848.0
Chungnam	12,400.0	–	3299.6	20,240.0	–	4622.6
Jeonbuk	–	–	718.4	–	–	718.4
Jeonnam	500.0	528.6	1514.7	850.0	528.6	2399.7
Gyeongbuk	–	–	–	–	–	800.0
Gyeongnam	7240.0	–	–	9240.0	–	920.0
Jeju	–	740.0	–	–	685.0	–

[a] Only the local government that has the electricity plants are included.

Table 4
The national averaged emission factors by per unit electricity generation fueled by oil, coal, and LNG (kg/MW).

Emission factor of power plant fuels	Oil	Coal	LNG
CO	251	1291	959
NO_X	885	4961	2991
SO_X	1367	1657	9
PM_{10}	19	145	31

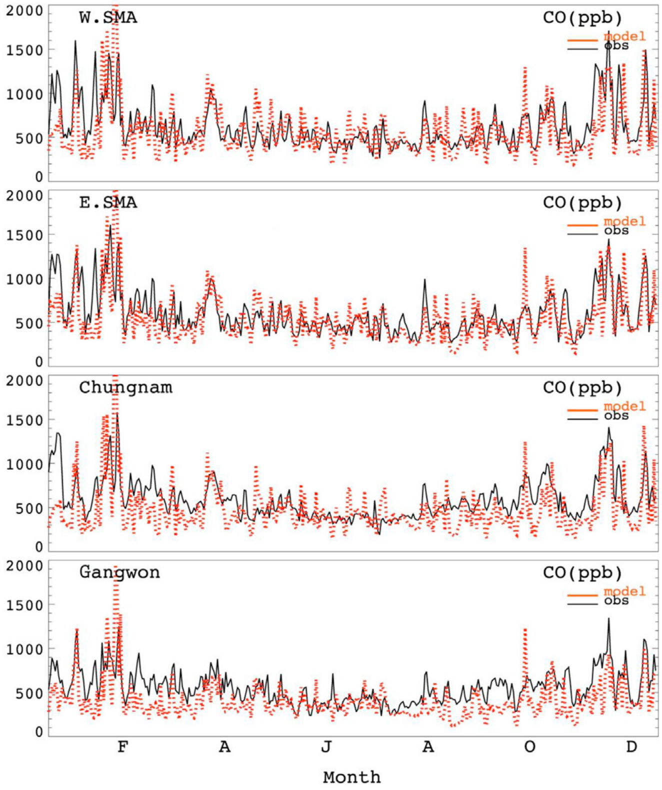

Fig. 7. The comparison between ground observations (black lines) and the model simulations (red dots) in terms of daily mean surface CO concentration at four regions (W. SMA, E. SMA, Chungnam, and Gangwon) in 2009. For the modeled CO, the bias was corrected by multiplying the scaling factor of 2. (Unit: ppbv). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

planned for Seoul, the national capital; however, LNG power plants in Gyunggi, which surrounds Seoul, are planned for the cities of Yeoju, Pocheon, and Pyungtaek. This will lead to a ~9000 MW increase in power supply compared to 2010. Gyunggi will close oil power generation facilities that will accounts for about 1400 MW of power capacity. Overall, annual emissions of CO, NO_x, SO_x, and PM_{10} in this region will change by about 12,000, 13,000, −1200, and 250 tonnes, respectively. These values represent relative changes of 10%, 9%, −8%, and 4%, respectively, compared to 2010.

In Chungnam, both coal and LNG power plants will be built, and the greatest emissions increases will be from coal plants in Dangjin and Taeahn (at the country's west coast, Fig. 4). These new plants will account for an additional 9000 MW of electric power capacity compared to 2010, producing additional 9000, 41,000, 23,000, and 1200 tonnes of CO, NO_x, SO_x, and PM_{10}, respectively, on an annual basis. These values represent changes of 16%, 33%, 41%, and 19%, respectively (Table 5).

3.2. Ground observations and evaluation of model performance

To evaluate the performance of the GEOS-Chem model, we compared ground observations to the model simulations for four regions (western SMA, eastern SMA, Chungnam, Gangwon) for 2009. Figs 7–10 compare the daily mean concentrations for each pollutant at the surface level. We excluded the results for SO_2 because the daily maximum values did not exceed the national

Table 5
The local emissions changes (%) from 2010 to 2027 according to the sixth BPE.[a]

(Unit: Percentage %)

Local government	CO			NO_x			SO_x			PM_{10}		
	Coal	LNG	Total	Coal	LNG	Total	Coal	LNG	Total	Coal	LNG	Total
Seoul	–	–	–	–	1	1	–	–	–	–	1	1
Busan	–	–	–	–	–	–	–	–	–	–	–	–
Incheon	7	(−7)	0	38	(−8)	30	56	1	57	20	(−3)	17
Ulsan	–	4	2	–	3	(−2)	–	–	(−3)	–	1	–
Gyunggi	–	10	10	–	10	9	–	–	(−8)	–	4	4
Gangwon	27	–	27	47	–	47	50	–	50	2	–	2
Chungnam	13	3	16	31	2	33	41	–	41	18	1	19
Jeonbuk	–	–	–	–	–	–	–	–	–	–	–	–
Jeonnam	1	3	4	2	1	3	1	–	1	–	–	–
Gyeongbuk	–	2	2	–	1	1	–	–	–	–	–	–
Gyeongnam	4	2	6	10	2	12	19	–	19	6	1	7
Jeju	–	–	–	–	–	–	–	–	(−2)	–	–	–

[a] Only the local government that has the electricity plants are included and negative values are in the parenthesis.

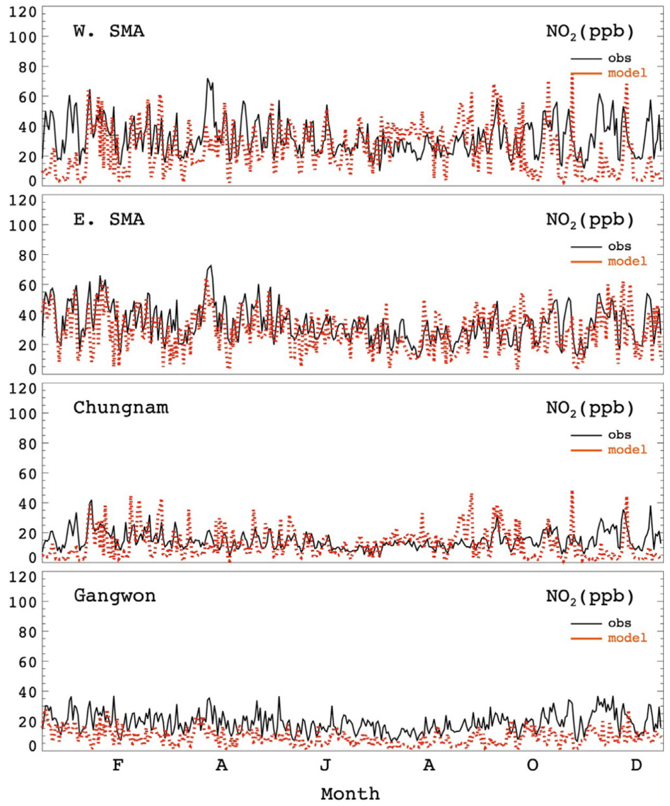

Fig. 8. The same as Fig. 7, but for NO_2 comparison (unit: ppbv).

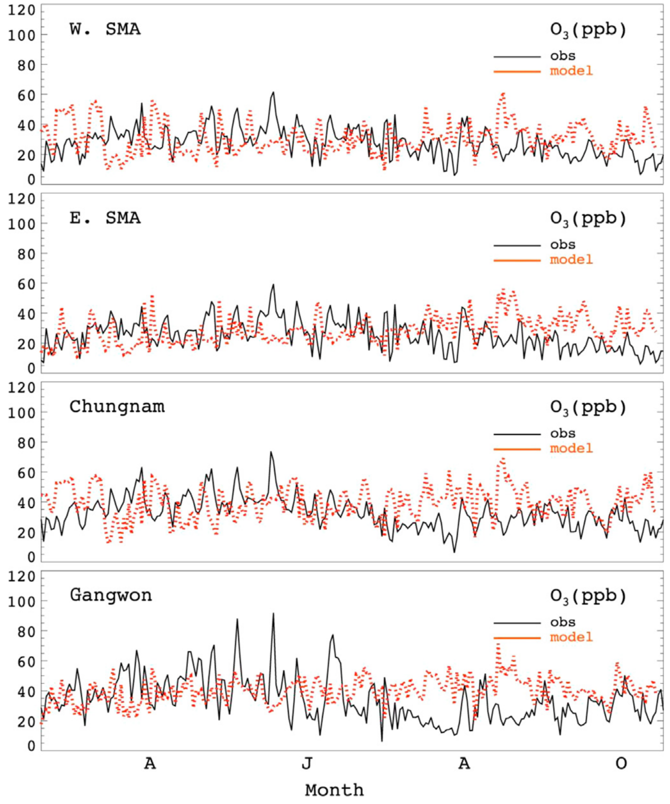

Fig. 9. The same as Fig. 7, but for O_3 comparison (unit: ppbv).

environment standard (150 ppbv/h) even when we applied the changes in emissions for 2027.

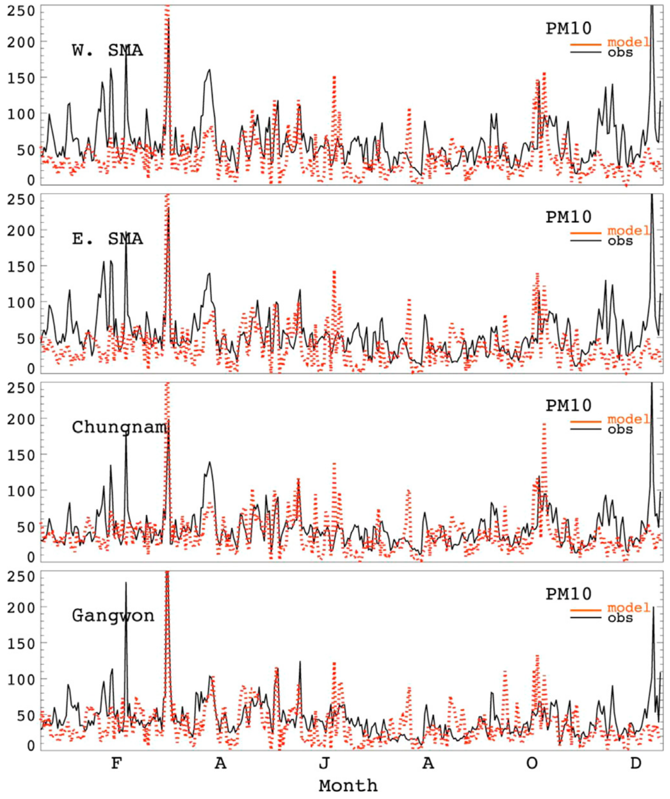

Fig. 10. The same as Fig. 7, but for PM_{10} comparison (unit: ppbv).

Table 6
Korean National Air Quality Standard (NAQS) for the major pollutants.

Pollutants	SO_2 (ppm)	CO (ppm)	Particular matter (μg/m^3)	
			PM_{10}	$PM_{2.5}$
	0.02/yr 0.05/day 0.15/h	9/8 h 25/h	50/yr 100/day	25/yr 50/day
Pollutants	NO_2 (ppm)	O_3 (ppm)	Lead (μg/m^3)	Benzene (μg/m^3)
	0.03/yr 0.06/day 0.1/h	0.06/8 h 0.1/h	0.5/yr	5/yr

Observation data indicated that the annual average CO emissions exceeded 550 ppbv for all four regions (Table 7). Considering that CO is a good proxy for biomass burning and anthropogenic emissions and its levels in clean areas are less than 100 ppbv, the observed concentration implies a large influence from anthropogenic emissions. In particular, the concentration in winter (November–February) was severe and often exceeded the national air quality standard (2500 ppbv) due mainly to its longer atmospheric lifetime by weaker photolysis. In addition, these high CO events could be greatly affected by long-range transport of air pollution from China because CO has a relatively long atmospheric lifetime (about a month).

GEOS-Chem results showed a moderate correlation with the observations in terms of the daily average (yearlong correlation coefficient [*R*] in the range of 0.5–0.6). In particular, it reproduced the high concentration events in the SMA in autumn and winter and reproduced the lower concentrations in summer caused by active photolysis (Fig. 7). However, the model gave a much lower annual average (about half the observed value). This could have been due to significant underestimations by the Streets inventory and the uncertainty associated with the diffusion algorithm under

Table 7
Comparisons of annual mean concentrations at the 4 regions between 2009 (observation) and 2027 based on the sixth BPE.

Annual mean concentrations		**CO** (ppbv)	**NO_2** (ppbv)	**O_3** (ppbv)	**PM_{10}** (µg/m^3)
W. SMA	Observations in 2009	619	32.3	23	60
	Changes in 2027 (model projection)	Δ(6)	Δ(3.4)	Δ(-2.0)	Δ(0.7)
E. SMA	Observations in 2009	600	33.5	20.9	54.6
	Changes in 2027 (model projection)	Δ(8.2)	Δ(7.2)	Δ(−3.2)	Δ(0.5)
Chungnam	Observations in 2009	589	15	28.9	46.9
	Changes in 2027 (model projection)	Δ(2.1)	Δ(1.4)	Δ(−1.4)	Δ(0.4)
Gangwon	Observations in 2009	553	19	30	44.7
	Changes in 2027 (model projection)	Δ(2.3)	Δ(1.4)	Δ(−1.6)	Δ(0.1)

vertical boundary conditions near the ground surface (Turquety et al., 2008; Park and Kim, 2014). In particular, the significant GEOS-Chem overestimation of CO except summer season was also shown at the eastern Chinese site by Wang et al. (2011), which can be explained by overestimation of the seasonality in the emissions inventory. The modeled data shown in Fig. 7 were corrected by applying a scaling factor of two.

NO_2 concentration is likely to be more affected by regional NO_x emission mainly due to its relatively shorter lifetime (1–2 days), which is clearly shown in Fig. 8. The annual mean NO_2 concentration over the SMA (west and east) was almost double that of the Chungnam or Gangwon regions (Fig. 8 and Table 7), mainly due to the emissions from a large number of motor vehicles (~8 million in 2009 [Ministry of Land, Infrastructure, and Transport of Korea, www.molit.go.kr/intro.do]) in the SMA. The annual average level of NO_2 for all of the observation stations in the SMA exceeded 30 ppbv. In particular, daily maximum concentration was often over 70 ppbv, higher than the daily maximum of Tokyo's roadside concentration (50 ppbv, Kodama et al., 2003). The model generally underestimated observations in terms of annual mean (by 4–9 ppbv), which again implies potential underestimation by the Streets inventory (Fig. 8). The underestimation of GEOS-Chem monthly NO_2 with Streets inventory has been also shown by Choi and Koo (2013) where GEOS-Chem simulation underestimated the sites of Acid Deposition Monitoring Network in East Asia (EANET) by 18% (1.6 ppbv).

Fig. 9 shows the data for O_3, a secondary air pollutant that is photochemically produced more actively in the summer. The O_3 had clear characteristics: the number of days exceeding NAQS (100 ppbv/h, Table 6) was higher in the SMA region (26, 50) than in the Chungnam (15) and Gangwon (11) regions (Table 8), where fewer emissions occurred as primary O_3 precursors. However, the annual mean concentration was significantly lower in the SMA (by 6–9 ppbv) than in Chungnam and Gangwon (Table 7). This may reflect a significant O_3 titration phenomenon in which remarkably high concentrations of NO directly react with O_3 at the surface over the SMA, as reported by previous studies such as Kim (2011) and Itahashi et al. (2013). The simulations did not reproduce the daily mean observations very well (R: 0.2–0.48), but did show the lower annual mean in the SMA compared to Chungnam and Gangwon. Despite these underestimations in annual mean values, the model generally overestimated observations by 8–12 ppbv, mainly due to a significant overestimation (> 15 ppbv) during the cold season (late autumn–winter, not shown) when photochemistry is likely to be less active. However, in terms of daily maximum values in the warm season (May–August), the simulated data showed generally lower concentrations (not shown). The GEOS-Chem overestimation over East Asia on a monthly basis has been identified by comparison of satellite column observations (Liu et al., 2006) and site observations (Wang et al., 2011) and the model discrepancy was attributed to the overestimation in the marine boundary layer or problems in simulating cloud optical properties (Liu et al., 2006; Wang et al., 2008, 2011). Thus, the relatively poor performance of the GEOS-Chem model in reproducing observed O_3 concentrations is a limiting factor for future projections due to the BPE.

The annual mean concentration of PM_{10} was in the range of 45–60 µg/m^3, and severe pollution events occurred when the daily mean value exceeded NAQS (100 µg/m^3) in the cold and dry season (October–April, Fig. 10). Considering the lifetime of PM_{10} (hours to days), those severe events could be associated with the long-range transport of air pollution from China or secondary production from the local precursors. This is also evident by the fact that the annual mean PM_{10} concentration in the SMA (western part of Korea, 55–60 µg/m^3) was higher than that of Gangwon (eastern part of Korea, 45 µg/m^3) (Fig. 4, Table 7), although the total PM_{10} emissions in Gangwon was four times greater than that in the SMA (KMOE, 2012). On the other hand, the higher PM_{10} concentration in the SMA than in Chungnam (both regions are located in western Korea, Fig. 4) implies the impact of domestic emissions from manufacturing industries and motor vehicle transportation. As shown in Fig. 10, the modeled daily mean values generally underestimated the values by 8–18 µg/m^3 but partly captured high pollution events (R: 0.3–0.55). The monthly GEOS-Chem PM_{10} comparison with EANET data by Choi and Koo (2013) also demonstrated that GEOS-Chem underestimated EANET data by 22% (11.58 µg/m^3).

3.3. *Projections of air quality based on the sixth BPE*

3.3.1. *Number of days exceeding the NAQS*

Next, we analyzed the number of days that exceeded the NAQS,

Table 8
The model projection of changes in number of days exceeding National Air Quality Standard (NAQS) in 2027 based on the sixth BPE. The base year is 2009.

Number of days exceeding NAQS		**CO**	**NO_2**	**O_3**	**PM_{10}**
W. SMA	Observations in 2009	75	93	50	306
	Changes in 2027 (model projection)	Δ8 (10.7%)	Δ21 (22.5%)	Δ3 (6%)	–
E. SMA	Observations in 2009	32	32	26	199
	Changes in 2027 (model projection)	Δ4 (12.5%)	Δ67 (209%)	Δ5 (19%)	–
Chungnam	Observations in 2009	17	–	15	109
	Changes in 2027 (model projection)	–	Δ8	Δ2 (13.3%)	Δ3 (2.8%)
Gangwon	Observations in 2009	16	10	11	95
	Changes in 2027 (model projection)	Δ3 (18.7%)	Δ24 (240%)	Δ6 (54.5%)	–

and considered the implications of their environmental health effects. Days in 2009 with excessive values were counted if at least one of the ground stations within each grid (Fig. 4) exceeded NAQS. In western SMA, more than 300 days had levels that exceeded the NAQS for PM_{10} (Table 8), indicating serious air pollution. Fifty days had excessive O_3 levels. As explained previously, this reflects the fact that the SMA is often affected by O_3 titration that terminates ground level O_3 as high NO_x emissions directly react with O_3, whereas O_3 concentration can often sharply increase in summer when the photochemical conditions are activated. The large amounts of NO_x emissions were related to the large number of days exceeding NAQS for NO_2, especially in western SMA (93 days, 100 ppbv/h, Table 8). The NAQS for CO was 2500 ppbv, and 75 days had levels exceeding the standard in western SMA (Table 8), which implies significant fossil fuel emissions in China and Korea.

3.3.2. *Projected number of days exceeding NAQS due to the sixth BPE (2027)*

Based on the GEOS-Chem simulation results with our projected emissions for 2027, the annual mean CO concentration will increase more in the SMA than in other regions (6–8 ppbv, Table 7). However, the increase will be less than 5% because current levels are already very high (Table 7). For NO_2, eastern and western SMA will show significant increases in the number of days on which levels will exceed NAQS (67 and 21, respectively) in 2027 (Table 8). This is likely to be the result of future additional coal and LNG power plants in adjacent regions of Incheon, Gyunggi, and Chungnam. Additional coal power plants in the Gangwon region are expected to significantly increase the number of days exceeding NAQS of NO_2 (24 days, Table 8). Despite a slight decrease in the annual average concentration of O_3 in 2027, the number of days exceeding NAQS will increase slightly, mostly within 5 days, which implies still-vigorous O_3 production in the warm season by an active photochemical environment. Similarly, no significant changes will occur in the number of days exceeding NAQS for PM_{10}. One reason for this is that the emissions factors for PM_{10} from electrical power generation are relatively lower (Table 4), thus the increase in emissions in Incheon city is only ~400 tonnes/year (17%). However, one needs to consider the fact that PM_{10} concentration over South Korea is already severely high with excessive levels most of the year.

In summary, O_3 and PM_{10}, which have the greater impact on environmental health among the atmospheric pollutants, will not significantly change in terms of the number of days on which levels exceed NAQS. However, the PM_{10} concentration is already excessively high and thus these results do not imply a marginal impact on air quality. There would be a marked increase in the number of days exceeding NAQS for NO_2 in the SMA and in Gangwon (Table 8), mostly due to new coal and LNG power plants in Incheon, Chugnam, Gyunggi, and Gangwon. Although the direct harmful effects of NO_2 on human health are not clear, this pollutant can stimulate the production of various secondary pollutants including acid rain and $PM_{2.5}$ (Turpin and Lim, 2001; Blanchard and Hidy, 2005; Kharol et al., 2013).

4. Uncertainties and limitations of this analysis and further research

This analysis involves some uncertainties and limitations, which should be considered when interpreting the results. First, not only domestic data, but also the East Asian air pollutant emission inventory, remain uncertain. The Streets emission inventory, which was used in this study, clearly underestimates the primary pollutants at the surface including CO and NO_2. Although the CAPSS emissions inventory for South Korea is continuously being improved, significant differences arise in some regions of Korea compared to other emissions inventories such as those of the Japanese National Institute for Environmental Studies (NIES) (Kim et al., 2013). Therefore, continuous verification by various models is necessary, such as the MICS-Asia project for Asian regions (Carmichael et al., 2008).

Second, Korea's complex atmospheric chemical environment associated with O_3 and PM should be reproduced well. For example, fluctuations in O_3 concentration have a complex relationship with those of NO_x concentration; therefore, various O_3 production sensitivities to primary pollutants under various conditions should be continuously investigated (Itahashi et al., 2013). Third, the GEOS-Chem model domain covers the regions that address the long-range transport effects over East Asia, but the relatively coarse size of the model grid ($\sim 50 \times 60$ km^2) limits its ability to represent the observation sites and the locations of power plants in South Korea. Fourth, it was difficult to estimate expected emissions amounts from newly constructed individual power plants that will be built in the future, partly because not all of the construction plans for power plants with applied technologies have been confirmed. Most current LNG plants in Korea use gas turbine and natural gas combined cycle technology (EPSIS, https://epsis.kpx.or.kr), and by 2027 the majority of the new LNG plants will apply the same power-generation technology. However, there will be more chance to apply a natural gas combine cycle in near future due to its much higher efficiency and lower emissions than a classical gas turbine. Increasing proportion of the advanced technology may lead to overestimation of our assumption of fixed current emissions factor for LNG plants.

In addition, there is the possibility of applying advanced technologies to supercritical coal-fired plants, which is one of the dominant coal-fired generation technologies in Korea. For example, a new coal-fired plant at Yeosu will apply circulating fluidized bed (CFB) combustion technology in 2016 (Yooshin & Co., Inc., 2011). New coal-fired plants are being planned for Taeahn and Seo-chun to introduce ultra-supercritical (USC) burning technology in 2016 and 2019, respectively (Korea Engineering Consultants Corporation, 2012, 2015). The planned USC technology for Taeahn will yield 3–5% greater efficiency for electricity generation compared to existing supercritical coal-fired plants in Taeahn (Korea Engineering Consultants Corporation, 2012) and USC is expected to be a major technology for coal-fired plants of Korea in the near future (Song, 2015). Therefore, although we used emissions factors as described in Section 3.1, differences may arise between estimated and actual emissions, which could potentially be mitigated by implementing advanced technologies in new power plants.

Finally, $PM_{2.5}$, which has a greater impact on human health and the complexity of the production processes, was not included in this study, because information on CAPSS is limited in terms of the changes in diverse precursor emissions to estimate $PM_{2.5}$. Additionally, the poor reproduction of GEOS-Chem for some compounds of $PM_{2.5}$ over South Korean region still needs to be improved (Lee et al., 2015a, 2015b). The uncertainty of emissions amounts, and production and extinction mechanisms, as well as unknowns, makes it difficult to reproduce accurate ambient $PM_{2.5}$ (Heald et al., 2005). It is also important to understand the transboundary effect of $PM_{2.5}$, which potentially has a greater influence associated with long-range transport than does PM_{10}. In addition, accurate calculation of an emissions factor for $PM_{2.5}$ according to future BPE is necessary to assess the environmental impact of energy policies in the future.

5. Conclusions and policy implications

We estimated the effects of the sixth BPE on the future air quality of Korea. Our major conclusions follow. First, we confirmed that the expansion of power plants in 2027 will significantly increase emissions from the electricity supply industry sector in the Incheon, Gyunggi, Chugnam, Gangwon, and Gyeongnam regions. In particular, the majority of additional plants will be coal-based, except in Gyunggi (LNG power plants); thus, these regions will have increased emissions of NO_x, CO, and PM_{10}.

Second, Korea currently has a severely large number of days on which PM_{10} levels exceed the NAQS. In the SMA, these currently number more than 50 days per year for O_3, NO_2, and CO. Based on these values, we estimate that the number of such days will increase by 21 and 67 days for NO_2 in western SMA (including Incheon, west Gyunggi, and west Seoul) and eastern SMA (eastern Seoul and eastern Gyunggi), respectively. This will potentially contribute to the formation of acid rain and fine particles that can affect the environment and human health. However, the number of days exceeding the NAQS for O_3 and PM_{10} are not expected to increase significantly (<6 days). Nevertheless, continuous investigation on the health effects of coal power plants, such emissions of heavy metals and harmful chemicals as well as primary pollutants, is necessary.

As planned by the sixth BPE, two-thirds of the new fossil fuel-driven power plants of Korea will be operated with coal by 2027. We only evaluated the influences of air pollutants that are currently measured and managed by the Korean Ministry of Environment (i.e., NO_x, CO, PM_{10}, and O_3). According to a report from the Health and Environment Alliance (HEAL, 2013), coal-fired power generation emits not only major air pollutants but also a variety of harmful tracers including formaldehyde (HCHO), heavy metals, and polycyclic aromatic hydrocarbons (PAHs), which could have serious effects on health. However, the Korean government's current plan for the future power supply does not consider the comprehensive environmental cost from those potential pollutant emissions. Therefore, continuous assessments of the effects of pollutant emissions on human health should be performed.

The Korean government implemented an air pollutant emission-cap management system in 2008, which allocates yearly allowances for NO_x and SO_x emissions to larger emitters (e.g., power plants). Voluntary implementation of emissions reduction has been expanded greatly and the allocations have been reduced continuously over SMA (KMOE, 2015). Although that policy has contributed to mitigating air pollution over SMA by prohibiting additional coal-fired power plants and permitting only LNG power plants within SMA, the potential environmental impact of coal-fired power plants near SMA (roughly 10–100 km from SMA) was not considered for the BPE as addressed by Yeo and Kim (2015). The study by Yeo and Kim (2015) considered the exposure to millions of people in the SMA and the effects of the transport of air pollutants from adjacent areas for a reassessment of the environmental cost (marginal external cost of emissions per kWh) of the sixth BPE. That study found that the new estimates of the environmental costs of coal power plants are much higher than the original estimations by the KMKE (2013), and that cost for coal power generation is greater than for LNG power plants. Our data also raise concerns about the potential harmful influence of increased NO_2 concentrations in the SMA region due to future coal power plants outside SMA.

In 2014, the US government announced the first guidelines for a carbon pollution reduction plan for current power plants (Clean Power Plan, CPP) as part of the government's Climate Action Plan (EPA, 2014a). The US government is planning to apply the CPP to 1000 thermal power plants across the nation that will reduce carbon emissions by 30% compared to 2005, and also reduce $PM_{2.5}$, SO_2, and NO_2 until 2030 (EPA, 2014b). The major implementation of the CPP is to transfer old power plants to ones that use LNG or alternative energy sources, and the resulting potential benefits include reduced rates of early death (from about 2700 to 6600; EPA, 2014b), childhood asthma, cardiac arrest, hospitalization rates, and labor hours.

The Korean national Emissions Trading Scheme (ETS) started in 2015, along with the 'National Greenhouse Gases Emissions Reduction Roadmap of Korea' announced in 2014, which are intended to meet its target of a 30% reduction in GHG emissions by 2020 (KMOE, 2015). Implementation of the national emissions reduction roadmap with ETS could have a significant negative impact on the Korean economy, due to reductions in the power sector (Lee et al., 2014). Therefore, introducing innovative technologies for better efficiency of power plants, utilization of renewable energy, and GHG processing are required to minimize the economic impact in Korea as suggested by Lee et al. (2014).

Recently, the Korean government announced the seventh Basic Plan for Long-Term Electricity Supply and Demand (7th BPE, 2015–2029) in July 2015, in which the proportion of coal-fired power plants for electricity generation will be reduced by ~2.5% (3740 MW), but that of nuclear power plants will be increased by ~1.1 % (3000 MW) (KMOTIE, 2015)). According to the 7th BPE, a plan for the construction of coal-fired power plants in Incheon (Yeongheung Island) will be revoked, which could benefit air quality over SMA. However, this cancellation caused conflicts among local stakeholders for environmental and economic reasons, and a new construction plan for nuclear power plants is now facing resistant from local communities, particularly in southeastern Korea (Bang, 2015; Seo, 2015), which is a critical issue to be resolved in the near future.

A more advanced evaluation of the potential health impacts of future power plants is urgently needed to propose and justify a cleaner power supply plan for Korea, along with a consideration of the comprehensive influence of emissions of a variety of hazardous compounds on the human body and exposed populations.

Acknowledgments

This subject is jointly supported by the National Research Foundation of Korea (No. NRF-2013S1A5B6043772) and Korea Meteorological Administration Research and Development Program under Grant CATER (No. 2012-3033). We thank Dr. Hyeong-Ah Jin at National Institute for Environmental Research (NIER) of Korea for supporting the information on national emissions inventory of Korea. We also thank Korea Environment Institute (KEI) for the institutional support for the research. The GEOS-Chem model is managed at Harvard University with support from the NASA Atmospheric Chemistry Modeling and Analysis Program.

References

Bang, S., 2015. Difference in stakeholder opinion between Song-do and Young-heung area for coal-fired plant construction plan in Incheon. edaily. Retrieved from: ⟨http://www.edaily.co.kr/news/NewsRead.edy?SCD=JA61&newsid=03204566609434192&DCD=A00106&OutLnkChk=Y⟩ (July 13, in Korean).

Blanchard, C.L., Hidy, G.M., 2005. Effects of SO_2 and NO_x emission reductions on $PM_{2.5}$ mass concentrations in the Southeastern United States. J. Air Waste Manag. Assoc. 55 (3), 265–272. http://dx.doi.org/10.1080/10473289.2005.10464624.

Carmichael, G.R., et al., 2008. MICS-Asia II: the model intercomparison study for Asia Phase II methodology and overview of findings. Atmos. Environ. 42, 3468–3490.

Chen, D., et al., 2009. Regional CO pollution in China simulated by the high-resolution nested-grid GEOS-Chem model. Atmos. Chem. Phys. 9, 3825e3839.

Choi, D.-R., Koo, Y.-S., 2013. An evaluation of the influence of boundary conditions from GEOS-Chem on CMAQ simulations over East Asia. J. Korean Soc. Atmos. Environ. 29 (2), 186–198. http://dx.doi.org/10.5572/KOSAE.2013.29.2.186.

Electric Power Statistics Information System of Korea. ⟨https://epsis.kpx.or.kr⟩ 2014.

EPA, 2014a. News Releases from Headquarters: EPA Progreses First Guidelines to

Cut Carbon Pollution from Existing Power Plants. EPA Press Office, United States (06/02/2014)http://yosemite.epa.gov/opa/admpress.nsf/bd4379a92cceceeac8525735900400c27/5bb6d20668b9a18485257ceb00490c98!OpenDocument.

EPA, 2014b. EPA Fact Sheet: Clean Power Plan. EPA Press Office, United States http://www2.epa.gov/carbon-pollution-standards/fact-sheet-clean-power-plan.

HEAL, 2013. The Unpaid Health Bill: How Coal Power Plants Make Us Sick www.env-health.org/IMG/pdf/heal_report_the_unpaid_health_bill_how_coal_power_plants_make_us_sick_final.pdf.

Heald, C.L., et al., 2005. A large organic aerosol source in the free troposphere missing from current models. Geophys. Res. Lett. 32, L18809. http://dx.doi.org/10.1029/2005GL023831.

Interagency of the Korean government, 2013. Synthetic measure of PM2.5 pollution (in Korean).

Itahashi, S., Uno, I., Kim, S., 2013. Seasonal source contributions of tropospheric ozone over East Asia. Atmos. Environ. 70, 204–217.

Kharol, S.K., Martin, R.V., Philip, S., Vogel, S., Henze, D.K., Chen, D., Wang, Y., Zhang, Q., Heald, C.L., 2013. Persistent sensitivity of Asian aerosol to emissions of nitrogen oxides. Geophys. Res. Lett. 40, 1021–1026. http://dx.doi.org/10.1002/grl_50234.

Kim, N.K., et al., 2013. Verification of NO$_x$ emission inventory over South Korea using sectorial activity data and satellite observation of NO$_2$ vertical column densities. Atmos. Environ. 77, 496–508.

Kim, Soontae, 2011. Ozone simulations over the Seoul Metropolitan Area for a 2007 June episode, Part V: Application of CMAQ-HDDM to predict ozone responses to emissions change. J. Korean Soc. Atmos. Environ. 27 (6), 772–790 (in Korean).

Kodama, Y., et al., 2003. Environmental NO$_2$ concentration and exposure in daily life along main roads in Tokyo. Environ. Res. 89 (3), 236–244.

Korea Engineering Consultants Corporation, 2012. Environmental Impact Assessment Report of Construction of the Tae-ahn Coal-fired Plants (9th and 10th). Korea Western Power & CO. Ltd, South Korea (in Korean).

Korea Engineering Consultants Corporation, 2015. Environmental Impact Assessment Report of Construction of the New Seo-Chun Coal-fired Plants. Korea Western Power & CO. Ltd, South Korea (in Korean).

Korean Ministry of Environment (KMOE), 2012. White paper of Korean Environment in 2012. KMOE (in Korean).

Korean Ministry of Environment (KMOE), 2015. Publication of Republic of Korea. Retrieved from: 〈http://www.me.go.kr/home/file/readDownloadFile.do?fileId=116670&fileSeq=2&openYn=Y〉.

Korean Ministry of Knowledge & Economy (KMKE, former KMOTIE of Korea), 2013. The Sixth Basic Plan for Long-term Electricity Supply and Demand (BPE) (2013–2027). Ministry of Knowledge & Economy. Retrieved from: 〈http://www.kpx.or.kr/english_new/down_data/market_report/The_6th.pdf〉.

Korean Ministry of Trade, Industry and Energy (KMOTIE), 2015. The Seventh Basic Plan for Long-Term Electricity Supply and Demand (7th BPE) (2015–2029). Ministry of Trade, Industry and Energy, South Korea (in Korean)http://www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_seq_n=157410&bbs_cd_n=81.

Le Quéré, C., et al., 2014. Global Carbon Budget 2014. Earth Syst. Sci. Data Discuss. 7, 521–610, OECD, 2008.

Lee, J.-I., Lee, I.-W., Kim, B.-H., 2015a. Generation expansion planning model supporting diverse environmental policies for reduction of greenhouse gases. ETRI J. 37 (2), 295–305.

Lee, S., Kim, K., Kim, Y., 2014. A Study on the Status of Greenhouse Gas Mitigation Policy Instruments and its Improvement (II). Korea Environment Institute, Sejong, Climate and Environmental Policy report of Korea Environment Institute.

Lee, H., Park, R., Shim, C., 2015b. Sensitivity analysis of PM2.5 and constraining BC emissions over Seoul Metropolitan Area with GEOS-Chem adjoint model. In: Megacity Air Pollution Studies (MAPS) Data Workshop. National Institute of Environmental Research, Incheon, 27 August.

Liu, X., Change, K., Sioris, C.E., et al., 2006. First directly retrieved global distribution of tropospheric column ozone from GOME: comparison with the GEOS-CHEM model. J. Geophys. Res. 111, D02308. http://dx.doi.org/10.1029/2005JD006564.

Na, Y., et al., 2013. Comparison of air pollution emission data for Asia. J. Clim. Res. 8 (2), 105–115, in Korean.

National Institute of Environmental Research (NIER), 2012. National Air Pollutant Emissions in 2010. NIER, Incheon (in Korean).

National Institute of Environmental Research (NIER), 2013. Annual Report of Air Pollution in 2012. NIER, Incheon (in Korean).

OECD, 2008. Environmental Data Compendium. 〈http://www.oecd.org/env/indicators-modelling-outlooks/oecdenvironmentaldatacompendium.htm〉.

Park, R.J., Kim, S.W., 2014. Air quality modeling in East Asia: present issues and future directions. Asia–Pac. J. Atmos. Sci. 50 (1), 105–120.

Private–Public Working Group of Korean Ministry of Trade, Industry & Energy (MOTIE), 2014. National Basic Energy Plan, MOTIE (in Korean).

Seo, K., 2015. Expanding resistance of local communities to new nuclear power construction plan in Sam-cheok area. News1. Retrieved from: 〈http://news1.kr/articles/?2355653〉 (July 31, in Korean).

Song, B., 2015. Latest technologies of coal-fired power plants. Energydaily. Retrieved from: 〈http://www.energydaily.co.kr/news/articlePrint.html?idxno=57957〉 (January 02, in Korean).

Streets, D.G., et al., 2006. Revisiting China's CO emissions after the Transport and Chemical Evolution over the Pacific (TRACE-P) mission: synthesis of inventories, atmospheric modeling, and observations. J. Geophys. Res. 111, D14306. http://dx.doi.org/10.1029/2006JD007118.

Turpin, B.J., Lim, H., 2001. Species contributions to PM2.5 mass concentrations: revisiting common assumptions for estimating organic mass. Aerosol Sci. Technol. 35, 602–610.

Turquety, S., et al., 2008. CO emissions and export from Asia: an analysis combining complementary satellite measurements (MOPITT,SCIAMACHY, and ACE-FTS) with global modeling. Atmos. Chem. Phys. 8, 5187–5204.

Wang, Y., Zang, Y., Hao, J., Luo, M., 2011. Seasonal and spatial variability of surface ozone over China: contribution from background and domestic pollution. Atmos. Chem. Phys. 11, 511–3525.

Wang, Y., McElroy, M.B., Munger, J.W., Hao, J., Ma, H., Nielson, C.P., Chen, Y., 2008. Variations of O$_3$ and CO in summertime at a rural site near Beijing. Atmos. Chem. Phys. 8, 6355–6363.

Yeo, M.J., Kim, Y.P., 2015. Sensitivity of the environmental costs of air pollution caused by SO$_x$, NO$_x$, and PM from power plants applied to the power mix configuration in South Korea. Air Qual. Atmos. Health . http://dx.doi.org/10.1107/s11869-015-0344-5.

Yooshin & Co., Inc., 2011. Environmental Impact Assessment Report of Construction of the 1st Yeo-su Coal-fired Plants. KOSEP & CO. Inc, South Korea (in Korean).

Zhang, H., et al., 2012. Simulation and validation of the aerosol optical thickness over China in 2006. Acta Meteorol. Sin. 26 (3), 330–344.

Zhang, Q., et al., 2009. Asian emissions in 2006 for the NASA INTEX-B mission. Atmos. Chem. Phys. 9, 5131–5153.