

Modeling the impact of reducing sulfur content of liquid fuels consumed by power plants on the air quality of Kuwait using AERMOD

Fahad M. Al-Fadhli*, Nawaf S. Alhajeri**, Ahmed Z. Aly* and Abdalrahman Alsulaili***

* Department of Chemical Engineering, College of Engineering and Petroleum, Kuwait University, Kuwait

** Department of Environmental Technology Management, College of Life Sciences, Kuwait University, Kuwait

*** Department of Civil Engineering, College of Engineering and Petroleum, Kuwait University, Kuwait

*Corresponding Author: alfadhli.f@ku.edu.kw

Submitted : 04/03/2022

Revised : 26/04/2022

Accepted : 05/05/2022

ABSTRACT

As part of Kuwait's plan to meet the country's long-term sustainability goals, a new refinery is being constructed with an objective of desulfurizing crude oil (CO) and heavy fuel oil (HFO) to a low sulfur content, S% (approximately 1% by mass). Since Kuwait's electric power system relies heavily on CO and HFO for electricity generation, the air quality impacts of this change in sulfur content should be investigated. In this work, three scenarios were examined and compared to the base case. The hourly SO₂ emissions of each scenario were simulated using an air quality model (AERMOD) to determine the spatial and temporal SO₂ dispersion for the year 2014. The three scenarios were developed based on lowering the sulfur content to 1% for HFO only, CO only, and both HFO and CO. The study results indicated that the annual SO₂ emissions were reduced by 75.6%, 12.5%, and 82.7% for the first, second, and third scenarios, respectively, compared to the base case scenario. The daily averages of SO₂ emissions of the first, second, and third scenarios were 57.7%, 12.4%, and 70.1% lower, respectively, compared to the base case. The reductions in the maximum region wide one-hour average SO₂ concentrations reached 47.4%, 24%, and 54.1% for the first, second, and third scenarios, respectively, compared to the base case. The numbers of hourly SO₂ exceedances were reduced by about 94%, 54%, and 100% for the first, second, and third scenarios, respectively, compared to the base case (7361 hourly SO₂ exceedances). The results of this analysis show the benefits of reducing the sulfur content of CO and HFO as mitigation strategy to reduce high ambient SO₂ concentrations.

Keywords: Ambient SO₂ concentrations; Heavy fuel oil; Crude oil; Power plants; Air dispersion modeling.

1. INTRODUCTION

The power and desalination plants in the State of Kuwait rely almost entirely on the combustion of fossil fuels to generate electricity and produce desalinated water. The Kuwait infrastructure has been systematically and historically conditioned to invariably depend on fossil fuels for energy production. Only four types of fossil fuels are consumed: natural gas, gas oil, crude oil (CO), and heavy fuel oil (HFO). The consumption of these types of

hydrocarbon fuels presents an environmental challenge in that their combustion emits several harmful air pollutants. The impact of the air pollutants on the air quality depends on the types and amount of the consumed fossil fuel, as well as the meteorological conditions. In Kuwait, choosing the specific amount of each type of fuel is based on their availability throughout the year (Alhajeri et al., 2018).

One of the major air pollutants associated with the combustion of fossil fuels in power plants is sulfur dioxide (SO₂). High SO₂ emissions cause negative impacts on the environment, humans, and animals. Specifically, high ambient SO₂ concentrations are associated with acid rain, smog, vegetation damage, and human health problems such as respiratory illness, aggravation of existing cardiovascular disease, and asthma (Flagan and Seinfeld, 2012; Cooper and Alley, 2010). Several studies investigated the dispersion of SO₂ emissions from power plants (Kho et al., 2007; López Villegas et al., 2004; Racoceanu and Capatina, 2006) and other sources (Abdul-Wahab et al., 2010; Abdul-Wahab et al., 2002; Abiye et al., 2016; Higazy et al., 2019; Kumar et al., 2006; Ozkurt et al., 2013) using air quality models around the globe. All the studies demonstrated the importance of using air quality models to investigate ambient SO₂ concentrations.

A few studies investigated the impact of SO₂ emissions from power plants on the air quality of the state of Kuwait. Al-Rashidi et al. (2005) studied the optimum locations for air quality monitors to capture excessive SO₂ emitted from power plants. They concluded that the SO₂ concentrations exceeded the Kuwait Environmental Public Authority (KEPA) standard limits in many areas, which necessitates the relocating of existing air quality monitors around Kuwait. Al-Azmi et al. (2008) investigated the impact of SO₂ emissions from three major power plants on the air quality of Kuwait. Their results showed that the daily and annual average SO₂ concentrations exceeded KEPA standards. Yassin and Al-Awadhi (2011) examined the impact of SO₂ emissions from two major power plants on the ambient air quality of Kuwait. Their study results confirmed that there are exceedances in the daily and hourly concentrations of SO₂. Alhajeri et al. (2019a) showed that switching from liquid fuels to natural gas in the power plants of Kuwait could reduce the SO₂ emissions by 98%. Al-Fadhli et al. (2019) simulated the dispersion of SO₂ from all power plants based on the hourly and annual average SO₂ emission rates. They verified that there are excessive SO₂ concentrations when using either emission rate (hourly average vs. annual average). However, using the hourly SO₂ emission rate would result in considerably more hourly exceedances compared to using the annual average SO₂ emissions. All the previous studies showed the importance of adopting mitigation strategies to reduce the SO₂ emissions from power plants to improve the air quality of Kuwait.

None of the previous studies have explored the air quality impact of reducing the sulfur content of the consumed fossil fuel in power plants as a mitigation strategy for improving the air quality. To address this problem, power plants in Kuwait will be used as a case study to examine the proposed mitigation strategy. Most of power plants in Kuwait rely heavily on HFO and CO to meet the power demands, and both fuels have significantly high sulfur content (Alhajeri et al., 2019b; Alhajeri et al., 2018). In earlier work, Al-Fadhli et al. (2019) examined the impact of fuel switching on minimizing the ambient SO₂ concentrations; however, this paper will focus on the potential benefits of reducing sulfur content of liquid fuels on the air quality. This study examined data in year 2014 since fuel consumptions on hourly basis were used to result in more accurate conclusions and simulate the hourly dispersion of SO₂ more precisely (Al-Fadhli et al., 2019). The data for hourly based consumption of hydrocarbon fuels by the power plants of Kuwait was first made available in 2014. In addition, the consumed fuel mix has not changed since power plants, in Kuwait, still rely on the same 4 types of fossil fuel to generate electricity, albeit at slightly different proportions depending on fuel availability (Alhajeri et al., 2018).

To minimize the air quality impact of SO₂ emissions, the state of Kuwait has decided to install a new refinery with an objective of reducing the sulfur content in HFO and CO to less than 1% by mass. Therefore, this work addresses the benefits of pre-desulfurizing the consumed liquid fuels at power plants, which can potentially reduce

the resultant SO₂ emissions. Specifically, this paper explores the air quality impacts of lowering the sulfur content in CO and HFO for power production purposes.

The impact of reducing the sulfur content of both CO and HFO is assessed independently through simulating four different scenarios: (i) a base case using the sulfur content as reported by the Ministry of Electricity and Water in Kuwait for 2014; (ii) lowering the sulfur content of HFO to 1%; (iii) lowering the sulfur content of CO to 1%; and (iv) lowering the sulfur content of both HFO and CO to 1%. Scenarios (ii)–(iv) will be compared to the base case scenario. The comparison will focus on four different aspects: (1) the annual and daily emissions throughout the year 2014, (2) the spatial and temporal patterns associated with the predicted maximum one-hour average SO₂ concentrations using AERMOD, (3) the hourly region-wide maximum SO₂ concentration, and (4) the number of times per hour the SO₂ concentration exceeds the KEPA standard limits throughout the one-year episode. Accordingly, conclusions will be drawn about the feasibility of the pre-desulfurization of HFO and CO as a mitigation strategy to reduce the ambient SO₂ concentrations.

2. METHODS

This section describes the geographical domain description, the meteorological conditions during the simulation period of 2014, and the air quality model used to run the simulations. Then, the development of the examined scenarios is discussed. Finally, the procedure to estimate the hourly SO₂ emission rates of each scenario is explained.

2.1 Geographical Domain Description

In this analysis, the area under investigation is Kuwait. The state of Kuwait has a total area of 17,818 km², where it is located in the Arabian Peninsula. It is bordered from the east by the Arabian Gulf, the north and northwest by Iraq, and south and southwest by Saudi Arabia. Kuwait has mostly flat Terrains. Kuwait relies on five main power plants for electricity generation, namely, Sabiya, Az-Zour South, Doha Complex, Shuaiba Complex, and Shuwaikh. These power plants have a total installed capacity of 15719 MW, of which 80% was used during peak demand in the summer of 2014 (MEW, 2015). The installed capacity of steam turbines is 9185.5 MW, whereas gas turbines contribute 3637 MW. The remaining capacity is a combination of steam and gas turbines running on combined cycle technology, which contribute 2896.5 MW and are installed at the two largest power stations (the Az-Zour South and Sabiya power plants). Figure 1 shows the geographical locations of the power plants used for energy production in Kuwait. All the power plants except Shuwaikh are dual-purpose, generating electrical power and producing desalinated water.



Figure 1. Power plant locations in Kuwait.

The available capacity at the power plants as of 2014 was 252, 1595.5, 3699, 5305.8, and 4866.7 MW for the Shuwaikh, Shuaiba complex, Doha complex, Az-Zour South, and Sabiya power plants, respectively. The Shuwaikh power plant was made up of 6 gas turbines with a capacity of only 42 MW each. The Shuaiba complex constituted 6 steam turbines with a unit capacity of 120 MW and 1 steam turbine with a 215.5 MW capacity, in addition to 3 gas turbines of 220 MW each. The Doha complex had a total of 15 steam turbines, 7 units at 150 MW each and 8 units at 300 MW each. The Doha gas turbines amounted to 11 units, 5 of which had an available capacity of 28.2 MW and 6 of which had 18 MW in available capacity. The Az-Zour South and Sabiya power plants, being the largest power plants in terms of installed capacity, were the only power plants with turbines running combined cycle technology. Az-Zour South had 17.5% of its total installed capacity running on combined cycle technology, whereas the Sabiya power station had a significantly larger 40% of its installed capacity from combined cycle technology. Both power stations had the same number of steam turbine units at equivalent installed capacities, 8 units at 300 MW each. However, Az-Zour South had 3 different sets of gas turbines, 8 units at 130 MW each, 4 units at 27.7 MW each, and 5 units at 165 MW each. This is compared to the two sets of gas turbines at the Sabiya power station, 6 units at 41.7 MW each and 4 units at 62.5 MW each as of 2014.

The stacks of the power plants were represented as point sources in the air quality model (AERMOD) at their respective locations. The parameters of each stack, such as the velocity, exit temperature, stack height, and base height, were collected from Al-Fadhli et al. (2019) (Table 1). The study area constituted a total of 13447 receptors, each with an area of 1 km². The study covered 112 and 118 km in the x and y directions, respectively. Moreover, the background SO₂ concentrations were assumed to be zero, and the terrain was assumed flat in the simulation since this analysis focuses on simulating and isolating the impact of power plants alone irrespective of other sources of air pollution.

Table 1. The base elevation, height, exit temperature, exit velocity, equivalent diameter, and number of stacks in the power plants of Kuwait (Al-Fadhli et al., 2019).

Power Plants					
Stack Parameters	Shuwaikh	Doha Complex	Shuaiba Complex	Az-Zour South	Sabiya
Base Elevation	6 m	6 m	24 m	4 m	15 m
Height	192 m	190 m	192 m	192 m	193 m
Exit Temperature	323 K	408 K	323 K	403 K	423 K
Exit Velocity	15 m/s	21 m/s	15 m/s	24 m/s	24 m/s
Equivalent Diameter	4 m	8m	4 m	6 m	6 m
Number of stacks	3	8	3	4	4

The fuel consumption rates were used to calculate the respective emissions at each power plant on an hourly basis. A monthly overview of the fuel consumption levels at the power plants in Kuwait is shown in Figure 2. The fuel-consumption peaks during the summer period are mainly due to cooling demands. The highest level of fuel consumption was in August 2014 at 79,600 trillion BTU. Natural gas made up 52% of the fuel consumption share at its peak, driven equally by consumption in steam and gas turbines. The consumption of gas oil in steam turbines was negligible, whereas, in gas turbines, its share was 11.9% of the total fuel consumption. Moreover, both crude and heavy fuel oils were only consumed by steam turbines. In August 2014, the crude and heavy fuel oils represented 17% and 19.3% of the total fuel consumption, respectively. The lowest monthly fuel consumption shares were in February 2014 at 37,500 trillion BTU. The HFO constituted 45.7% of the fuel consumed during February, which is significantly larger than its fuel share in the summer. The natural gas consumption in steam turbines was stable at 26% of fuel consumption. However, the natural gas consumption in gas turbines was only 8.2% of the fuel consumption. The fuel consumption shares for gas oil and CO stood at 8.4% and 11.5%, respectively, during February.

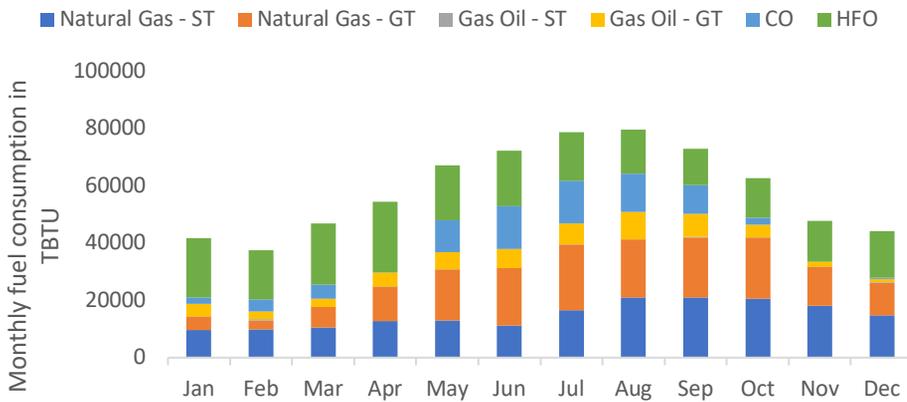


Figure 2. Monthly fuel consumption for 2014 in trillion BTU.

2.2 Meteorological Conditions

Meteorological data are continuously recorded by Kuwait International Airport, which was the source for the meteorological conditions of 2014 used as the input to the air quality model. The data included meteorological parameters that are descriptive of the weather such as wind speed, wind direction, temperature, and atmospheric pressure. These parameters are necessary to determine the atmospheric stability class and simulate the dispersion of SO₂ emitted from power plants.

In 2014, the prevailing wind direction was from the northwest with an average wind speed of 6.2 m/s. Calm winds prevailed for 8.7% of the study period. The average temperature and pressure during 2014 were 28.45°C and 100.3 kPa, respectively. The highest recorded wind speed, temperature, and pressure were 18.6 m/s, 49.9°C, and 102 kPa, respectively. Moreover, the minimum temperature and atmospheric pressure were 2.15°C and 98.7 kPa, respectively.

2.3 Air Quality Model

In this work, AERMOD was used to simulate the dispersion of SO₂ emissions from the power plants in Kuwait. AERMOD is an air quality model that is based on the assumption of a steady-state dispersion plume. It was created by a collaborative group of scientists at the American Meteorological Society (AMS) and US-Environmental Protection Agency (USEPA). It has consistently proven superior to other dispersion modeling packages, specifically for steady-state plume models in various studies (Mohan et al., 2011; Hanna et al., 2001). Moreover, a field study compared the results obtained through AERMOD to those of a database of 17 field studies (Perry et al., 2005). The field studies were of a diverse nature and included those from complex and flat terrains, rural and urban conditions, and surface and elevated emissions. The study results indicated that the performance of AERMOD was superior compared to other dispersion models. More recently, Al-Fadhli et al. (2019) have shown reasonable performance for AERMOD in predicting airborne SO₂ concentrations by validating model's output across 3 different air quality monitoring stations across Kuwait.

2.4 Scenarios Definition

To assess the impact of lowering the sulfur content in the fuel consumed by power plants on the air quality of Kuwait, four scenarios were developed based on the sulfur content (S%) of HFO and CO.

- I. Base case scenario: the estimated hourly SO₂ emission rate of each power plants was estimated and then simulated to be the base case of the other scenarios. The details of the validation and development of the base case were discussed in a previous publication (Al-Fadhli et al., 2019).
- II. First scenario: the sulfur content of the HFO was reduced to 1% by weight, and the sulfur content of the other fuels was the same as the base case.
- III. Second scenario: the sulfur content of the CO was reduced to 1% by weight, and the sulfur content of the other fuels was the same as the base case.
- IV. Third scenario: the sulfur contents of both the CO and HFO were reduced to 1% by weight, and the sulfur content of the other fuels was the same as that of the base case.

All the developed scenarios were simulated using AERMOD to estimate the spatial and temporal distribution of the ambient SO₂ hourly concentrations.

2.5 Emission Rates and Factors

To calculate the emission rates, the hourly unit-based fuel consumption rates were calculated and multiplied by the respective emission factors. The detailed approach for obtaining the hourly consumption rates for 2014 was discussed in Alhajeri et al. (2018, 2019b). The emission factors were estimated using USEPA AP-42 for the designated fuel type and combustion technology at the respective power plants (USEPA, 1995). Equations 1–7 were used to determine the hourly emissions rates. The hourly fuel consumption rates (FC) were reported in MMBtu per hour for every fuel type (natural gas, gas oil, CO, and HFO) for the specific combustion technology (steam turbine or gas turbine) and were multiplied by the corresponding emission factor. The average SO₂ emission factors for natural gas, gas oil, CO, and HFO were 0.000246, 0.064, 1.03, and 1.52 kg of SO₂ per MMBtu of fuel consumed, respectively, for steam turbines. For gas turbines, the average emission factors of natural gas and gas oil were 0.0108 and 0.0783 kg of SO₂ per MMBtu of fuel consumed, respectively. The sulfur content was manipulated to reflect the different scenarios being studied.

$$\begin{aligned}
 SO_2 \text{ hourly emission rates (kg per hour)} \\
 &= FC_{NG_ST} * EF_{NG_ST} + FC_{NG_GT} * EF_{NG_GT} + FC_{GO_ST} * EF_{GO_ST} \\
 &+ FC_{GO_GT} * EF_{GO_GT} + FC_{CO_ST} * EF_{CO_ST} + FC_{HFO_ST} * EF_{HFO_ST}
 \end{aligned} \tag{1}$$

$$EF_{NG_ST}(\text{kg per MMBtu}) = 0.000246 \tag{2}$$

$$EF_{GO_ST}(\text{kg per MMBtu}) = 0.374 * S\% \tag{3}$$

$$EF_{CO_ST}(\text{kg per MMBtu}) = 0.389 * S\% \tag{4}$$

$$EF_{HFO_ST}(\text{kg per MMBtu}) = 0.402 * S\% \tag{5}$$

$$EF_{NG_GT}(\text{kg per MMBtu}) = 0.425 * S\% \tag{6}$$

$$EF_{GO_GT}(\text{kg per MMBtu}) = 0.458 * S\% \tag{7}$$

Where FC_{NG_ST} = Hourly consumption rate of natural gas in steam turbines
 EF_{NG_ST} = Emission factor of the consumed natural gas in steam turbines
 FC_{NG_GT} = Hourly consumption rate of natural gas in gas turbines
 EF_{NG_GT} = Emission factor of the consumed natural gas in gas turbines
 FC_{GO_ST} = Hourly consumption rate of gas oil in steam turbines
 EF_{GO_ST} = Emission factor of the consumed gas oil in steam turbines
 FC_{GO_GT} = Hourly consumption rate of gas oil in gas turbines
 EF_{GO_GT} = Emission factor of the consumed gas oil in gas turbines
 FC_{CO_ST} = Hourly consumption rate of crude oil in steam turbines
 EF_{CO_ST} = Emission factor of the consumed crude oil in steam turbines
 FC_{HFO_ST} = Hourly consumption rate of heavy fuel oil in steam turbines
 EF_{HFO_ST} = Emission factor of the consumed heavy fuel oil in steam turbines
 S% = Percentage of sulfur content by mass in the consumed fuel.

The emission factors varied on a monthly basis due to changes in the sulfur content of fuels supplied to the power plants. Table 2 illustrates the monthly average of the fuel sulfur content in 2014 (MEW, 2015). Heavy fuel oil's sulfur content oscillates between a maximum of level of approximately 4% and a minimum of 3.5%. Gas oil's sulfur content is much lower, at a monthly maximum of only 0.314%. The sulfur content of natural gas is even lower, at a maximum of only 0.085%.

Table 2. Monthly averaged sulfur content (wt%) for all types of fuels consumed at power plants in Kuwait in 2014.

Month	Natural Gas (S%)	Gas Oil (S%)	CO (S%)	HFO (S%)
Jan	0.03	0.127	2.645	3.6112
Feb	0.015	0.164	2.645	3.6185
Mar	0.01	0.201	2.645	3.515
Apr	0.015	0.159	2.645	3.8906
May	0.01	0.314	2.645	3.9671
Jun	0.01	0.167	2.645	3.5871
Jul	0.035	0.167	2.645	3.5871
Aug	0.035	0.134	2.645	3.92
Sep	0.01	0.17	2.645	4.0518
Oct	0.015	0.159	2.645	3.54
Nov	0.035	0.144	2.645	4.0592
Dec	0.085	0.144	2.645	4.0592

3. RESULTS

This section discusses the simulation results for all scenarios and compares them to the base case scenario. The total annual and daily SO₂ emissions levels throughout 2014 for all of the scenarios are estimated. Then, the spatial and temporal patterns associated with each scenario in terms of the maximum SO₂ one-hour average concentrations are presented as a contour map of the study area. Finally, the region-wide one-hour SO₂ concentrations and the number of hourly SO₂ exceedances predicted by AERMOD are discussed for each scenario.

3.1 Annual Emissions

The annual emissions of SO₂ for 2014 were estimated to be 409,700 tonnes for the base case scenario. However, by reducing the sulfur content of HFO alone in the first scenario, annual emissions were 75.6% lower at 173,400 tonnes of SO₂, whereas reducing the sulfur content of CO alone (second scenario) did not result in a significant drop in the annual emissions of SO₂, which were only 12.5% lower compared to the base case. Moreover, the estimated emissions from achieving a 1% sulfur content for both fuels (third scenario) reached 122,600 tonnes of SO₂ for 2014, which represents 82.7% reduction in SO₂ emissions.

3.2 Daily Emissions

The average daily emissions throughout 2014 were 1,122 tonnes of SO₂ per day for the base case. This is in comparison with a lower 475, 983, and 336 tonnes per day for the first, second, and third scenarios, respectively. Figure 3 shows the daily SO₂ emission rates for the four scenarios throughout 2014. The emissions generally peaked through the summer due to the higher energy demand of air conditioning.

Moreover, reducing the sulfur content of HFO alone (the first scenario) could achieve a significant reduction in the SO₂ emissions, as shown in Figure 3. The average daily emission rate was 58% lower for this scenario compared to the base case. The maximum daily emission rate was 911 tonnes of SO₂ per day, whereas the minimum emission rates was 172 tonnes of SO₂ per day. This is due to the use of cleaner fuels such as natural gas and gas oil. However, the percent reductions in emissions for the first scenario were lower during the summer season and late winter, which is due to the relatively higher consumption of natural gas and CO compared to HFO during the same period.

In contrast, lowering the sulfur content of CO alone (the second scenario) resulted in only a slight reduction in SO₂ emissions. The average daily emission rate was only 12.4% lower compared to the base case for the second scenario. This is because the CO consumption is much lower compared to HFO consumption at the power plants (Alhajeri et al., 2018). This is also evident from Figure 3, where, for most of the year (except for the summer period), the percent reduction is nearly zero. The maximum daily emission rate stood at 1709 tonnes per day, whereas the minimum emission rate was 562 tonnes of SO₂ per day. This suggests that reducing the sulfur content in HFO (the first scenario) is more effective in reducing SO₂ emission rates.

The emissions for the third scenario were significantly lower through the entire period (~70% lower). The maximum daily SO₂ emission rate for the third scenario was 542 tonnes per day, and the minimum emission rate was 172 tonnes per day.

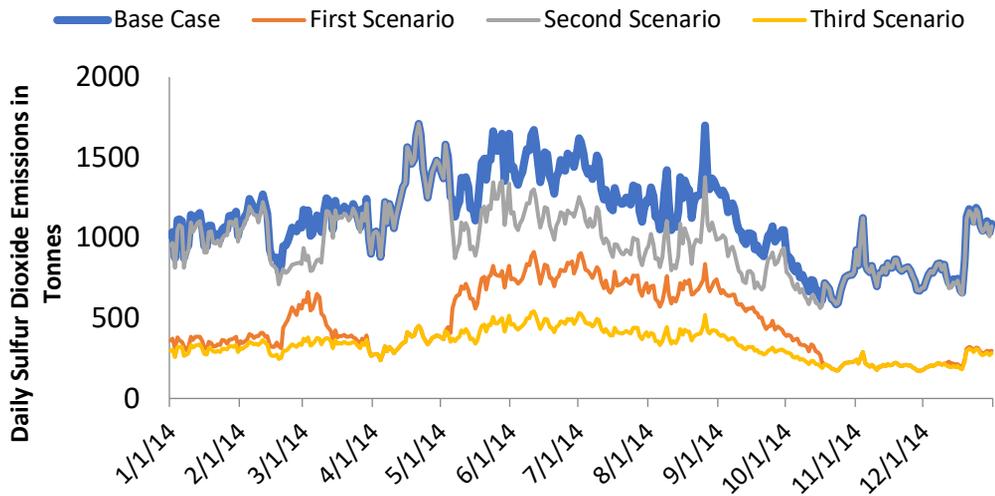


Figure 3. SO₂ daily emissions for all scenarios in 2014.

3.3 Atmospheric Dispersion

The predicted concentrations largely mirror the results obtained by assessing the daily emissions in that the third scenario has shown the lowest airborne concentrations across the study area, followed by the first scenario, and finally the second scenario (in comparison to the base case). Figure 4 shows a contour map of the maximum one-hour average concentrations of SO₂ over the study area for the (a) base case, (b) first scenario, (c) second scenario, and (d) third scenario. Figure 4a indicates that the SO₂ concentrations exceed KEPA SO₂ hourly standard limit (444 µg per m³) in large residential areas for the base case. Examples of the residential areas that are exposed to high levels of SO₂ include Doha, Al-Jahra, Qairawan, and Sulaibikhat. Lowering the sulfur content of HFO only results in a significant reduction in the maximum one-hour average SO₂ concentrations over the study area compared to the base case as shown in Figures 4a and 4b. The maximum one-hour average concentrations reached 919 µg per m³ in the first scenario, while the base case was much higher at 1747 µg per m³. Although still higher than the KEPA standard limit, several of the residential areas exposed to high SO₂ concentrations in the base case had much lower SO₂ concentrations in the first scenario. An example is the Al-Jahra residential area, which had a maximum one-hour average concentration of approximately 600 µg per m³ in the base case, compared to 180 µg per m³ in the first scenario. Moreover, Sabiya's impact on the air quality seems to have been significantly diminished as the sulfur content of HFO is reduced to 1%.

In contrast, the impact of reducing the sulfur content of crude oil alone (second scenario) on the ambient SO₂ concentrations is significantly lower compared to reducing the sulfur content of HFO (first scenario). This is shown by the contour map of the predicted maximum one-hour average SO₂ concentrations in Figure 4c. The maximum hourly SO₂ concentration for the case of 1% sulfur content in crude oil independent of heavy fuel oil (the second scenario) reached 1328 µg per m³. The simulation results showed that there is no significant reduction in the number of residential areas affected by high SO₂ concentrations compared to the base case, unlike when reducing the sulfur content in HFO (the first scenario).

The air quality impact is clearly different for the third scenario compared to the base case, as shown in Figure 4d. The estimated maximum one-hour average SO₂ concentration was reduced by 54% compared to the base case (801 $\mu\text{g per m}^3$). This occurred in the vicinity of the Doha complex and was far from the nearby residential areas. The simulation results indicated that the ambient SO₂ hourly concentrations were reduced significantly compared to the base case scenario over the residential areas as illustrated in Figure 4d.

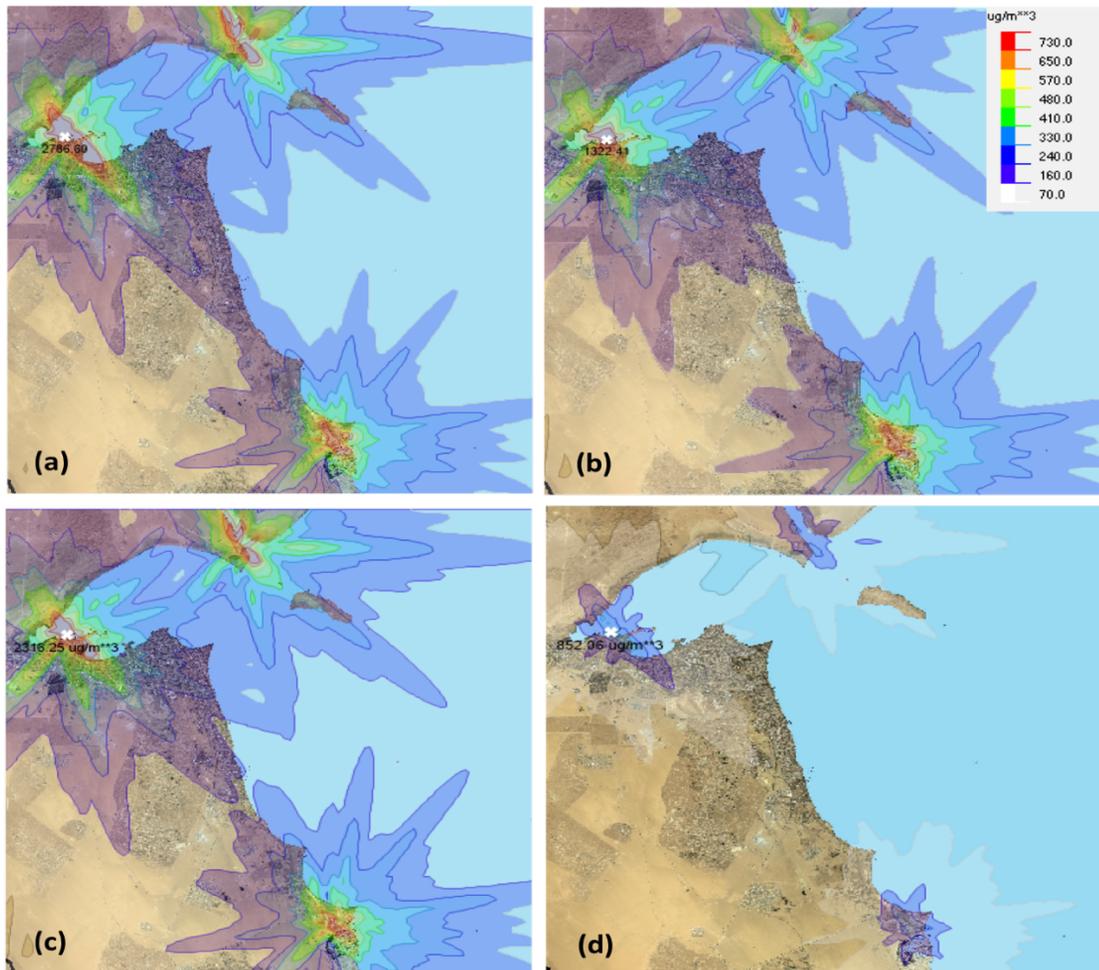


Figure 4. Spatial distribution of the maximum one-hour average SO₂ concentrations for the (a) base case, (b) first scenario, (c) second scenario, and (d) third scenario.

3.4 Maximum Region-Wide Hourly Concentrations

The maximum region-wide SO₂ one-hour concentrations were practically lower throughout all hours of the day for all scenarios compared to the base case. Figure 5 shows the maximum region-wide one-hour SO₂ concentration of each scenario for each hour over the course of the day (24 hours) for the entire study period. The maximum region-wide SO₂ one-hour concentrations were reduced for all scenarios compared to the base case.

The maximum hourly concentrations were higher than the KEPA limit of $444 \mu\text{g}/\text{m}^3$ during 13 of the 24 hours of the day, as shown by the red line in Figure 5 for the base case and the first and second scenarios. Specifically, the concentrations exceeded the KEPA limit between the 6th and the 18th hours of the day. The estimated maximum region-wide one-hour average SO_2 concentrations were 1747, 919, and $1328 \mu\text{g}/\text{m}^3$ for the base case, first, and second scenarios, respectively. The third scenario resulted in the highest reduction in the maximum region-wide hourly concentrations, which was 54% ($801 \mu\text{g}/\text{m}^3$) compared to the base case. Comparatively, the maximum region-wide one-hour concentrations for the first and second scenarios are still higher than those of the fuel switching scenario that was detailed in Al-Fadhli et al. (2019). The third scenario shows a very promising result in comparison with the fuel switching scenario.

The simulation results illustrate the significant impact of HFO fuel related SO_2 emissions on system-wide emissions when compared to CO fuel.

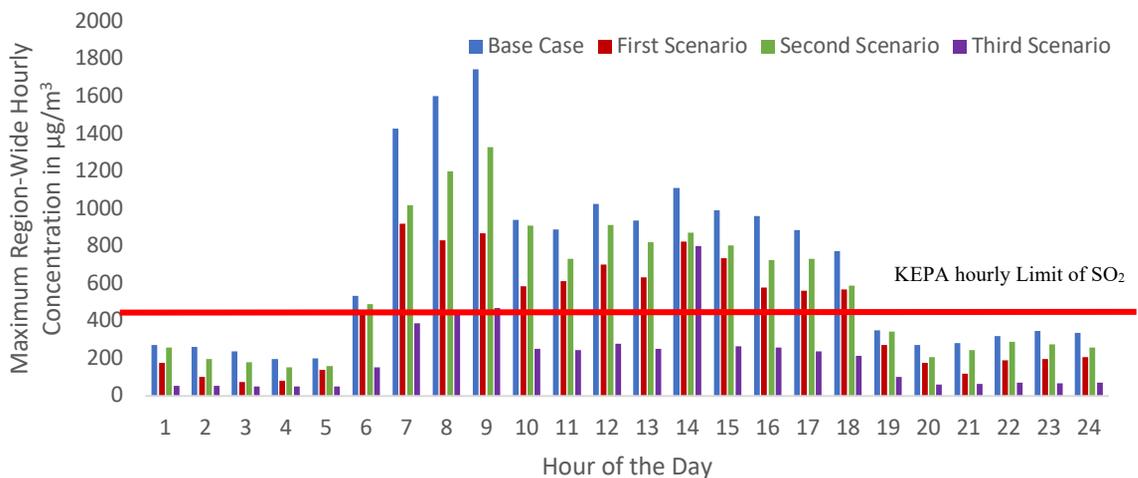


Figure 5. Maximum region-wide one-hour SO_2 concentrations for the base case and all three scenarios.

3.5 Hourly SO_2 Exceedances

The hourly SO_2 exceedance results largely mirror what was observed by assessing the contour maps and the daily emissions. Figure 6 illustrates the estimated number of SO_2 one-hour concentrations that exceed the KEPA standard limits ($444 \mu\text{g}/\text{m}^3$) over all the receptors during the simulated period. When the sulfur content for both crude and heavy fuel oil was 1% (the third scenario), the hourly exceedances were effectively eliminated, decreasing from a total of 7361 exceedances in the base case to only 2 exceedances. In addition, the first scenario resulted in a 94% reduction in the hourly SO_2 exceedances when the sulfur content of HFO was reduced to 1%. However, the second scenario contributed to a much lower reduction in the hourly SO_2 exceedances, where the number of hourly exceedances was 3350 SO_2 exceedances. Table 3 summarizes the main results of simulating the four scenarios using AERMOD. This compares favorably with results of the fuel switching scenario at Al-Fadhli et al. (2019), where the fuel switching scenario resulted in 675 exceedances.

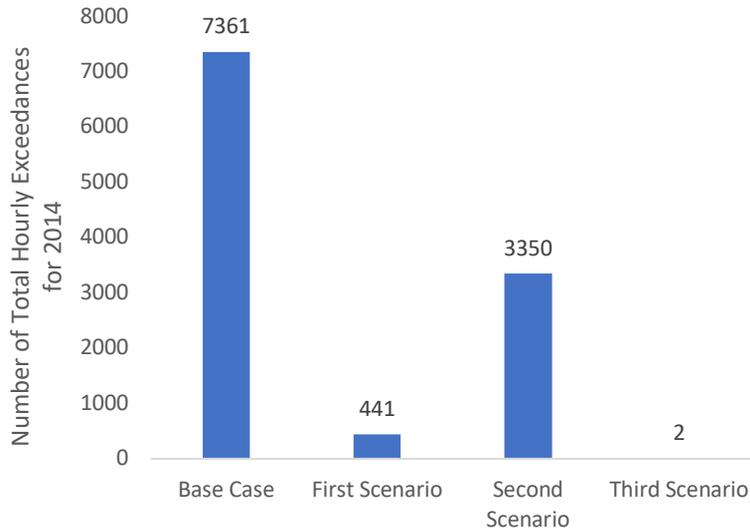


Figure 6. Total number of hourly SO₂ exceedances in 2014 for the base case and all three scenarios.

Table 3. Analysis results of the base case, first, second, and third scenarios, respectively.

	Base Case	First Scenario	Second Scenario	Third Scenario
Annual SO ₂ emissions (tonnes)	709700	173400	620989	122600
Average daily SO ₂ emissions (tonnes/day)	1122	475	983	336
Maximum one-hour average SO ₂ concentration (µg/m ³)	1747	919	1328	801
Hourly SO ₂ exceedances	7361	441	3350	2

4. CONCLUSIONS

The impact of SO₂ emissions on the air quality of Kuwait was analyzed for different scenarios corresponding to different sulfur content levels in crude and heavy fuel oils that are consumed by power plants. AERMOD was used to simulate the dispersion of SO₂ emissions for each scenario investigated in this study.

A total of three scenarios were studied and compared to the base case. The first scenario corresponds to changing the sulfur content of HFO to 1%. Similarly, the second scenario corresponds to reducing the sulfur content of CO to 1%, and the third scenario represents reducing the sulfur content of both fuels to 1%. There were four different aspects by which all the scenarios were analyzed: i) the annual and daily emissions throughout 2014, ii) the spatial patterns associated with the maximum one-hourly SO₂ concentrations, iii) the maximum region-wide SO₂ one-hour

concentrations, and v) the total number of times the predicted hourly SO₂ concentrations exceeded the KEPA standard limits throughout 2014. The study used the most recently available data (2014) for hourly fuel consumption to simulate the resultant dispersion of SO₂ from power plants in Kuwait subject to the different scenarios. The same mix of the four types of fossil fuels is still used, in 2020, for electricity generation, albeit with slightly different proportions depending on fuel availability.

This analysis showed that HFO's contribution to SO₂ emissions was much larger compared to CO fuel. The annual and the average daily SO₂ emission rates were significantly reduced when the sulfur content of HFO was reduced to 1%. Therefore, reducing the sulfur content of only CO has an insignificant impact on SO₂ emissions compared to that of HFO. The reduction in the annual SO₂ emissions for the first, second, and third scenarios in 2014 was 75.5%, 12.5%, and 82.7%, respectively, compared to the base case. The average daily SO₂ emissions were 1122, 475, 983, and 336 tonnes per day for the base case and the first, second, and third scenarios, respectively. In the base case, several residential areas were identified to have hourly SO₂ concentrations that exceeded the KEPA limit. The SO₂ hourly concentrations of these residential areas were effectively reduced when the sulfur content of HFO was reduced to 1%. The maximum region-wide one-hour average SO₂ concentrations were 1747, 919, 1328, and 801 µg/m³ for the base case and the first, second, and third scenarios, respectively. The number of hourly SO₂ exceedances was reduced by 94%, 54%, and 100% for the first, second, and third scenarios, respectively, compared to the base case (7361 hourly SO₂ exceedances).

The analyses reported here may have uncertainties in estimating the impact of reducing the sulfur content of liquids fuels on the air quality due to several reasons. AERMOD simulates SO₂ emissions assuming steady-state dispersion with no atmospheric reactions across the study area. The meteorological conditions at Kuwait International Airport were assumed to be representative of the weather conditions over the study area. Averaged emission factors based on the USEPA AP-42 were used to estimate the hourly emission rates across power plants in Kuwait and used as input to the model. Nevertheless, the study results indicated that reducing the sulfur content of both crude and heavy fuel oils or HFO alone would significantly mitigate the air quality impacts associated with high ambient SO₂ concentrations in Kuwait and similar regions.

REFERENCES

- Abdul-Wahab S, Sappurd A, Al-Damkhi A.** Application of California Puff (CALPUFF) model: a case study for Oman. *Clean Technologies and Environmental Policy* 2010; 13: 177-189.
- Abdul-Wahab SA, Al-Alawi SM, El-Zawahry A.** Patterns of SO₂ emissions: a refinery case study. *Environmental Modelling & Software* 2002; 17: 563-570.
- Abiye O, Sunmonu L, Ajao A, Akinola O, Ayoola M, Jegede O.** Atmospheric dispersion modeling of uncontrolled gaseous pollutants (SO₂ and NO_x) emission from a scrap-iron recycling factory in Ile-Ife, Southwest Nigeria. *Cogent Environmental Science* 2016; 2: 1275413.
- Al-Azmi BN, Nassehi V, Khan A.** Impact of emissions from power stations on the ambient air quality of selected urban areas in Kuwait. *American Journal of Environmental Sciences* 2008; 4: 558.
- Al-Fadhli FM, Alhajeri NS, Aly AZ, Allen DT.** The impact of power plant emission variability and fuel switching on the air quality of Kuwait. *Science of The Total Environment* 2019; 672: 593-603.
- Al-Rashidi M, Nassehi V, Wakeman R.** Investigation of the efficiency of existing air pollution monitoring sites in the state of Kuwait. *Environmental pollution* 2005; 138: 219-229.

- Alhajeri NS, Al-Fadhli FM, Aly AZ.** Unit-Based Emissions Inventory for Electric Power Systems in Kuwait: Current Status and Future Predictions. *Sustainability* 2019b; 11: 5758.
- Alhajeri NS, Al-Fadhli FM, Aly AZ, Reimers A, Webber ME.** Electric Power System Profile in Kuwait: Electricity and Water Generation, Fuel Consumption and Cost Estimation. *ACS Sustainable Chemistry & Engineering* 2018; 6: 10323-10334.
- Alhajeri NS, Dannoun M, Alrashed A, Aly AZ.** Environmental and economic impacts of increased utilization of natural gas in the electric power generation sector: Evaluating the benefits and trade-offs of fuel switching. *Journal of Natural Gas Science and Engineering* 2019a; 71: 102969.
- Cooper, C. D.; Alley, F. C.,** Air pollution control: A design approach. Waveland press: 2010.
- Flagan RC, Seinfeld JH.** Fundamentals of air pollution engineering: Courier Corporation, 2012.
- Hanna SR, Egan BA, Purdum J, Wagler J.** Evaluation of the ADMS, AERMOD, and ISC3 dispersion models with the OPTEX, Duke Forest, Kincaid, Indianapolis and Lovett field datasets. *International Journal of Environment and Pollution* 2001; 16: 301-314.
- Higazy M, Essa KS, Mubarak F, El-Sayed E-SM, Sallam AM, Talaat MS.** Analytical study of Fuel switching from Heavy Fuel oil to Natural Gas in clay brick factories at Arab Abu saed, Greater Cairo. *Scientific reports* 2019; 9: 1-10.
- Kho WF, Sentian J, Radojevic M, Tan C, Law P, Halipah S.** Computer simulated versus observed NO₂ and SO₂ emitted from elevated point source complex. *International Journal of Environmental Science & Technology* 2007; 4: 215-222.
- Kumar A, Dixit S, Varadarajan C, Vijayan A, Masuraha A.** Evaluation of the AERMOD dispersion model as a function of atmospheric stability for an urban area. *Environmental Progress* 2006; 25: 141-151.
- López Villegas M, Tzintzun Cervantes M, Iniestra Gómez R, Garibay Bravo V, Zuk M, Rojas Bracho L,** et al. Evaluating the Impacts of Power Plant Emissions in Mexico. 9th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Garmisch-Partenkirchen, 2004, pp. 1-4.
- MEW.** Statistics Department and Information Center of the Ministry of Electricity and Water of Kuwait "Statistical Year Book ", 2015.
- Mohan M, Bhati S, Sreenivas A, Marrapu P.** Performance evaluation of AERMOD and ADMS-urban for total suspended particulate matter concentrations in megacity Delhi. *Aerosol and Air Quality Research* 2011; 11: 883-894.
- Ozkurt N, Sari D, Akalin N, Hilmioglu B.** Evaluation of the impact of SO₂ and NO₂ emissions on the ambient air-quality in the Çan–Bayramiç region of northwest Turkey during 2007–2008. *Science of the total environment* 2013; 456: 254-266.
- Perry SG, Cimorelli AJ, Paine RJ, Brode RW, Weil JC, Venkatram A,** et al. AERMOD: A dispersion model for industrial source applications. Part II: Model performance against 17 field study databases. *Journal of applied meteorology* 2005; 44: 694-708.
- Racoceanu C, Capatina C.** Cross-boundary pollution due to the activity of a thermal power station. *Journal of the University of Chemical Technology and Metallurgy* 2006; 41: 103-106.
- USEPA. U.S. Environmental Protection Agency,** " AP-42: Compilation of Air Emission Factors ". 2017, 1995.
- Yassin MF, Al-Awadhi MM.** Impact of Sulfur Dioxide Emissions of Power Stations on Ambient Air Quality. *Environmental Engineering Science* 2011; 28: 468-475.