Reduction of NO_x and SO₂ Emissions by Shore Power Adoption

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ABSTRACT

Shore power systems, an alternative energy source to ships at berth, have the potential to improve air quality at ports and surrounding areas. This study assessed the reduction of four major air pollutants: PM₁₀, PM_{2.5}, NO_x, and SO₂, from adopting shore power at the Port of Kaohsiung. The reduction was assessed in two scenarios, S1 and S2, with a capacity to provide shore power to 342 and 780 ships at berth, respectively. The emissions from the ships were estimated based on the operation loads of the auxiliary engines, average time at berth, and emission factors. Additionally, the AERMOD model was used to simulate the ground-level dispersion of the four pollutants to the surrounding urban areas. The simulation results showed that the elevated areas in the city were vulnerable to ship emissions, especially for NO_x. The maximum simulated contribution at ground level from S1 and S2 were 78.8 µg m⁻³ and 147 µg m⁻³ for NO_x, and 20.1 µg m⁻³ and 42.5 µg m⁻³ for SO₂, respectively; while the results for PM₁₀ and PM_{2.5} were insignificant. The reduction benefit was then calculated as the ratio of the simulated air pollutant concentration to the observed concentration at the local air quality monitoring station. The highest reduction benefit of shore power adoption at the port was for NO_x and SO₂ emissions, with average reduction benefits of 8.70% ± 2.10% and 11.74% ± 2.95%, respectively. In conclusion, shore power adoption at the Port of Kaohsiung would greatly reduce air pollution in the port city, especially in residential areas, and be considered a sustainable solution to improving air quality and combating climate change.

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1 INTRODUCTION

Maritime transport, which accounts for 80–90% of all global trade (Balcombe *et al.*, 2019; Sadiq *et al.*, 2021), is a notoriously major emitter of nitrogen oxides (NO_x), sulfur dioxides (SO₂), and particulate matter (PM). For instance, Zhong *et al.* (2020) reported that international shipping accounted for 16% of the total anthropogenic SO₂ emissions in 2014. Nearly 70% of these emissions occur near coastlines, posing immediate environmental and human health risks to the coastal populations (Fileni *et al.*, 2019; Liu *et al.*, 2019; Chen *et al.*, 2020; Kuzu *et al.*, 2020). Port cities especially, with high population densities, are more susceptible to ship emissions (Lin *et al.*, 2018; Jayaratne *et al.*, 2020).

In response, the international maritime organization (IMO) spearheaded the development of the international treaty, Marine Pollution Convention (MARPOL) Annex VI, to address ship emissions

and progressively reduces air pollution from ships. Effective on January 1st, 2020, the treaty mandates ships to use fuel with a maximum sulfur content of 0.5% m/m. This adoption has led to significant SO₂ emission reductions from docking ships. Wan *et al.* (2019) estimated that SO₂ emissions could be reduced by 74.0% when ships use 0.5%-sulfur instead of 2.7%-sulfur fuel while docking at the Shanghai Port. The treaty also limits NO_x emissions from ships with power outputs > 130 kW, which has resulted in a gradual decrease in NO_x emissions. For instance, Tier III medium-speed auxiliary diesel engines have an emission factor of 2.8 g of NO_x kWh⁻¹ compared with 13 g of NO_x kWh⁻¹ of Tier I engines (POLB, 2018). However, more sustainable measures should be considered to curb air pollution further, including adopting shore power systems.

Shore power systems, also known as cold ironing, provide electrical power for ships hoteling at berths. Shore power saves fuel consumption and prevents the resultant emissions relating to the mining, transporting, and combustion of fuel. Therefore, the adoption of shore power is seen as an environmental best practice for turning ports green and sustainable (Chang and Wang, 2012). Winkel *et al.* (2016) estimated total health benefits of 2.4 billion Euros for 2020 and carbon dioxide reductions of 0.8 megatons if all the European ports adopted shore power. As of June 2020, 45 major global ports in America, Europe, and Asia have shore power capacity. The Port of Kaohsiung, one of the busiest ports globally, is one of these ports. Currently, there are only two container terminals that have shore power systems. It is important to evaluate the benefits before increasing the shore power capacity.

Dispersion models have been used in several studies to assess air pollution at ports, industrial, and urban areas (Fallah-Shorshani *et al.*, 2017; Merico *et al.*, 2017). They are considered a cost-effective and time-saving approach for quantifying the deterministic relationship between emissions and concentrations of pollutants in the atmosphere (Frilingou and Bouris, 2020; Kuzu *et al.*, 2020). AERMOD is a commonly used air dispersion model that is recommended and promulgated by the U.S. EPA since 2006. The model has been widely applied to study NO_x, SO₂, and PM emissions in urban areas (Kesarkar *et al.*, 2007; Cook *et al.*, 2008; Zou *et al.*, 2009; Johnson *et al.*, 2010). AERMOD performs well, especially in elevated urban areas, because the boundary layer structure is considered (Langner and Klemm, 2011; Tsai *et al.*, 2019).

Therefore, this study aims to assess the environmental benefits of using shore power at the Port of Kaohsiung. The assessment was based on the 2019 ship calling information and meteorology data from the nearby air quality monitoring stations. AERMOD was used to simulate the dispersion of NO_x, SO₂, and PM emissions from the docking ships. Findings from this study will help decision-makers further develop shore power in the Port of Kaohsiung and similar global ports.

2 MATERIAL AND METHODS

2.1 Study Area

The Port of Kaohsiung, located on the southwest coast of Taiwan (Fig. 1), is one of the busiest shipping hubs globally. The port covers 26.6 kilometers of waterline with a total area of 1,871 hectares. It is situated in a low elevation area ranging from 1 to 10 m above mean sea level. The elevation gradually rises to 30 m at the city center. Higher terrain strips are scattered around the port and city center, influencing the dispersion of air pollutants from ground sources. The port has a total of 121 operational berths that can simultaneously accommodate 155 ships. It received 17,307 ships in 2019, including containers, bulk cargo, and cruise ships, and handled 10.43 million twenty-foot equivalent units (TEU) of cargo (TIPC, 2020).

2.2 Estimation of Ship Emissions

During berthing, the main engine is shut off, and the auxiliary engine is used to provide power to the ship for lighting, communication, refrigeration, and powering other electrical devices. Therefore, the NO_x, SO₂, PM₁₀, and PM_{2.5} emissions from the ships in this study were estimated based on the auxiliary engine. Eq. (1) was used to estimate the ship emissions (POLA, 2019). The correction factors to adjust for fuel used and control measures were based on actual operation data collected from Taiwan International Ports Corporation.

$$E = \text{Energy} \times EF \times FCF \times CF \quad (1)$$

where E refers to the NO_x , SO_2 , PM_{10} , and $\text{PM}_{2.5}$ emissions from the auxiliary engine (g); Energy , calculated using Eq. (2), refers to the energy output of the engine (kWh); EF is the emission factor of the engine (g kWh^{-1}); FCF is the fuel correction factor (dimensionless); and CF is the control factor for emission reduction technologies (dimensionless). The emission factors for each pollutant of the auxiliary engines were adopted from the Port of Long Beach 2017 Air Emission Inventory (POLB, 2018) and were based on 2.7%-sulfur heavy fuel oil (HFO), as shown in Table S1. The fuel correction factors, presented in Table S2, were used to adjust the ship emissions to 0.5%-sulfur marine gas oil (MGO), as mandated by law (MOTC, 2018). The control factor was considered as one, assuming all ships use low-sulfur fuel instead of air pollution control devices.

$$\text{Energy} = \text{Load} \times \text{Activity} \quad (2)$$

where Load is the auxiliary engine operational load (kW) and Activity refers to the average time at berth (h). The load power (Table S3) from related research was used for ships with unavailable auxiliary engine information. The average time at berth was calculated from the reported average time of container ships docking at the port terminals (Table S4).

Two terminals, Evergreen Marine Corporation (T1) and Yang Ming Marine Transport Corporation (T2), shown in Fig. 1 have had high-voltage shore power systems since 2012 (Tseng and Pilcher, 2015). Currently, four to six ships can plug into the shore power systems simultaneously, depending on the ship size. Therefore, two scenarios (S1 and S2), based on ship activities in 2019 at the two terminals, were used in this study to evaluate the air pollution reduction from shore power adoption at the port. In scenario S1, we assume to provide shore power to all local container ship calls (342), while in scenario S2, we assume the capacity is expanded to cater to all the international container ship calls (780) that visited the Port of Kaohsiung. All these ships are equipped with shore power connecting devices.

Fig. 1. The location of the study area, Port of Kaohsiung, and the Taiwan EPA air quality monitoring stations, on the southwest coast of Taiwan.

2.3 Dispersion Model

AERMOD model was used to simulate the dispersion of the four air pollutants from the auxiliary engine emissions to the surrounding area. However, under the assumption that all ships calling at the port use 0.5%-sulfur marine gas oil (MGO), as mandated by law (MOTC, 2018), only emissions from MGO were used in the simulation. A model domain of 35 km × 35 km that covered the whole Kaohsiung metropolitan area was set to assess the effect of these emissions on the resident (Fig. 1). The dispersion was calculated in steady-state using the Gaussian plume method. Table 1 contains basic information about the emission point sources. The emission rates of the pollutants were based on their annual emissions calculated using Eq. (1) and were assumed to be steady throughout the year due to the unavailable data on berthing schedules.

Terrain information was acquired from Web GIS SRTM3 (Shuttle Radar Topography Mission) with a resolution of 90 m using the AERMAP pre-processor provided by AERMOD. All the coordinates followed Universal Transverse Mercator (UTM) system. A grid with uniform spaces of 200 m was generated with a total of 30625 receptors. The required parameters for surface meteorology included temperature, humidity, pressure, wind direction, wind speed, ceiling height, cloud cover, precipitation, and global radiation. All the meteorological factors were on hourly basis over 2019 and were collected from a nearby meteorological station (Siaogang air quality and meteorological station) which provided comprehensive meteorological information (Fig. 2). The upper air data

Table 1. The basic information of the emission sources.

Item	Unit	Value
Base elevation	m	28.8
Release height	m	24.8
Gas exit temperature	°C	178
Stack diameter	m	1.016
Velocity	m s ⁻¹	23.8

Note: The data was obtained from Evergreen Marine Corporation and Yang Ming Marine Transport Corporation.

Fig. 2. The wind rose diagram for 2019 at the E3 Air quality monitoring station. The prevalent directions were WNW and N, and the most frequent wind speed class was 2.1 to 3.6 m s⁻¹.

was approximated using the AERMET estimation tool, similar to Jesse *et al.* (2011). Within the model domain, only two types of surface characteristics were defined: urban and water. The values of surface parameters on Albedo, Bowen ratio, surface roughness (Table S5) were adopted from a previous study in Kaohsiung (Tsai and Tsuang, 2005).

3 RESULTS AND DISCUSSION

3.1 Emissions from Ships at Berth

Based on Eqs. (1) and (2), the emissions of NO_x, SO₂, PM₁₀, and PM_{2.5} were estimated for the two scenarios in 2019 using 2.7%-sulfur (HFO) and 0.5%-sulfur (MGO) fuels (Table 2). These emissions represent the amount of pollutants released from the auxiliary engines when the ships are at berth. In general, the emissions increased proportionally with the number of ship calls from the two scenarios. Additionally, the emissions in the case of HFO were higher than those from MGO, especially for SO₂, as shown in Table 2.

By switching from HFO to the lighter fuel with lower sulfur content (MGO), SO₂ had the highest reduction (81.5%), followed by PM₁₀ (75.0%) and PM_{2.5} (71.1%). However, the NO_x emissions were not as significant (~6.0%). Similarly, Wan *et al.* (2019) estimated that SO₂ and PM₁₀ emissions could be reduced by 74.0% and 68.1%, respectively, if ships docking at the Port of Shanghai used 0.5%-sulfur instead of 2.7%-sulfur fuel. They also reported that switching to low-sulfur fuel minimally reduced NO_x emissions (4.7%). Commonly, SO₂ emissions are generated during the combustion of sulfur-containing fuels, while PM emissions are influenced by the ash and sulfur content of the fuel and moisture (Reşitoğlu *et al.*, 2014). Therefore, switching to lower sulfur fuel can substantially reduce SO₂ and PM emissions (Han, 2010; Chu *et al.*, 2019; Fan and Gu, 2019).

Contrarily, NO_x emissions are formed via the oxidation of the nitrogen content in the fuel (fuel NO_x) and nitrogen portion in the air (thermal NO_x) (Ryu *et al.*, 2016; Yang *et al.*, 2019). HFO usually has higher nitrogen content than MGO, for example, Winnes and Fridell (2009) reported that the nitrogen content in HFO and MGO was 0.46% and < 0.05% wt, respectively. Thermal NO_x is more sensitive to combustion temperature, with high formation rates associated with high combustion temperatures (Haglund, 2008). Sarvi *et al.* (2008) reported that distillate light fuel oil has a higher cetane number than HFO, which causes earlier ignition and thus less time for pre-ignition mixing. This results in lower combustion temperature and lower NO_x emissions. Therefore, both fuel NO_x and thermal NO_x could explain why NO_x emissions were estimated to reduce only by 6% when switching from HFO to MGO.

With the adoption of shore power systems, all the emissions from auxiliary engines can be eliminated when the ship is at berth. For instance, when switching from HFO to shore power, SO₂ and NO_x emissions would be significantly reduced by as much as 345 tons and 238 tons for the year 2019, respectively. On the contrary, NO_x emissions would have the highest reductions of 94.1% (Fig. 3) when switching from MGO to shore power, followed by PM_{2.5} (29.0%), PM₁₀ (25.0%) and SO₂ (18.5%).

Fig. 4 compares the emissions from the two scenarios (S1 and S2) to the emission inventory of Kaohsiung city's off-road transportation sector. In the case of switching from HFO to shore power (Fig. 4(a)), SO₂ would exhibit the highest reductions (as much as 15.9%) in the off-road transportation sector, followed by PM_{2.5} (6.64%), PM₁₀ (6.55%), and NO_x (3.64%), respectively. When we assumed all ships use MGO (Fig. 4(b)), NO_x would have the highest reductions of up to 3.43% when shore power is adopted. Therefore, shore power systems are an effective pollution prevention solution for curbing these emissions from ships at berth.

Table 2. Estimated ship emissions in 2019 (tons) from using HFO and MGO for the two scenarios.

Subject	Scenarios	PM ₁₀	PM _{2.5}	NO _x	SO ₂
HFO (2.7%-sulfur)	S1	13.2	11.0	106	148
	S2	35.6	29.3	238	345
MGO (0.5%-sulfur)	S1	3.31	3.18	99.8	27.4
	S2	8.90	8.49	224	63.9

Fig. 3. The emission reductions (%) by switching from HFO to MGO and from MGO to shore power.

Fig. 4. The reduction (%) by switching from (a) HFO to shore power and (b) MGO to shore power. The calculations were based on the mass balance between estimated emission released from using HFO or MGO and total emission retrieved from Kaohsiung City's off-road transportation sector (Table S6), whereby emissions from ship and port activities accounted for 98.7%.

3.2 Ship Emissions Disperse into the Surrounding Environment

Fig. 5 depicts the simulated dispersion of PM₁₀, PM_{2.5}, NO_x, and SO₂ from the port to the surrounding areas for scenario S2 (the S1 scenario results are presented in Fig. S1) based on the

emissions from using MGO (0.5%-Sulfur). The contour lines represent the ground concentration levels of the air pollutants. From the simulations, the ship emissions reached the city center and could thus pose a health risk to the city residents. High concentrations of air pollutants were observed in the areas with high elevations. On the other hand, low and flat areas had lower concentrations. These observations suggest pollutant accumulation in the elevated areas and enhanced pollution dispersion in the low and flat areas. The stagnant air condition and pollution accumulation of elevated lands have also been reported in previous studies (Chow *et al.*, 2013; Miao *et al.*, 2019).

Particularly, NO_x emissions were dispersed over the whole urban center, with the hourly average concentrations below $10 \mu\text{g m}^{-3}$ in the low and flat areas and from 10 to $147 \mu\text{g m}^{-3}$ in the hilly areas for S2. Similarly, SO_2 dispersed over the entire urban area, and the highest concentrations

Fig. 5. The simulated dispersion of the daily average concentrations of (a) PM_{10} and (b) $\text{PM}_{2.5}$; and the hourly average concentrations of (c) NO_x and (d) SO_2 for the S2 scenario. The contour levels depict the ground concentration of the pollutants, and the average concentrations are shown on each contour line. The orange-colored contours have the highest concentrations, while the purple-colored contours have the lowest concentrations. The red transparent shape is the Port of Kaohsiung area.

Table 3. The simulated maximum concentrations ($\mu\text{g m}^{-3}$) of the four pollutants at ground level for the two scenarios.

Scenarios	PM ₁₀ (daily average)	PM _{2.5} (daily average)	NO _x (hourly average)	SO ₂ (hourly average)
S1	0.50	0.48	78.8	20.1
S2	0.62	0.59	147	42.5
Taiwan EPA air quality standards	100	35	100	75

were recorded in the hilly areas. The hourly average concentrations in the urban area were below $4 \mu\text{g m}^{-3}$ and from 4 to $42.5 \mu\text{g m}^{-3}$ in the hilly areas for S2. Table 3 presents the maximum concentration in terms of the daily average for PM₁₀ and PM_{2.5} and the hourly average for NO_x and SO₂. The values were compared to the Taiwan EPA air quality standards (TEPA, 2012). The PM concentrations were much lower than the standards in both scenarios. In scenario S2, the maximum NO_x concentration exceeded the standards ($100 \mu\text{g m}^{-3}$) 1.5 times, while SO₂ remained below the standards ($75 \mu\text{g m}^{-3}$) in both scenarios.

The effect of ship emissions from these two scenarios would have a considerably negative impact on the city's air quality, especially the elevated areas surrounding the city center. Therefore, solutions such as shore power should be adopted to mitigate or eliminated air pollution from hoteling ships.

3.3 Estimated Ambient Air Pollution Reduction Benefit from Shore Power Adoption

The contribution of the ship emissions at berth to the actual air pollutant concentrations from nearby monitoring stations was assessed using Eq. (3) (Merico *et al.*, 2017; Murena *et al.*, 2018). This contribution represents the reduction benefit of shore power adoption to the surrounding environment.

$$RB(\%) = \frac{C_{s_i}}{C_{o_i}} \times 100 \quad (3)$$

where *RB* is the reduction benefit to the environment by using shore power, *C_{s_i}* is the concentration simulated by AERMOD at the Taiwan EPA air quality monitoring station (E1, E2, E3) for air pollutant *i* from ship emissions, and *C_{o_i}* is the concentration observed at the Taiwan EPA air quality monitoring station for air pollutants *i*. The concentrations used were average hourly concentrations for NO_x and SO₂ and daily average concentrations for PM₁₀ and PM_{2.5}.

The three monitoring stations (E1, E2, and E3) were located nearby the port, as shown in Fig. 1. Monitoring stations E2 and E3 are close to industrial complexes, including oil refineries, steel mills, power plants, and semiconductor industries, while E1 is located in a residential area. In 2019, the stations further south, closer to industrial activities, recorded higher concentrations (*C_{E3}* > *C_{E2}* > *C_{E1}*) for NO_x and SO₂ (Table S8). However, the concentrations of PM₁₀ and PM_{2.5} were similar for all three monitoring stations.

Table 4 presents the estimated air pollution reduction benefits from adopting shore power at the three Taiwan EPA air quality monitoring stations. Generally, NO_x and SO₂ had the highest reduction benefits in both scenarios. In scenario S2, the average reduction benefits were $8.70\% \pm 2.10\%$ and $11.74\% \pm 2.95\%$ for NO_x and SO₂, respectively. The highest reductions were observed at E1 (11.05% and 15.06% for NO_x and SO₂, respectively). This monitoring station is located in a crowded residential area; therefore, these benefits will alleviate human health risks due to exposure to these pollutants. In summary, implementing shore power at the port will improve the air quality, especially for NO_x and SO₂ ambient concentrations, at the port and the urban area.

3.4 Hindrance to Shore Power Adoption

Shore power systems have considerable environmental benefits. They can improve the air quality in port cities and mitigate climate change when renewable sources are used (Han, 2010). However, some obstacles should be considered during the planning and implementation of shore power systems. These obstacles can broadly be divided into cost and regulation enforcement.

Table 4. The estimated air pollution reduction benefits (%) from shore power adoption for the two scenarios at the three Taiwan EPA air quality monitoring stations nearby the port.

Scenarios	Taiwan EPA station	PM ₁₀	PM _{2.5}	NO _x	SO ₂
S1	E1	0.02%	0.04%	5.42%	7.53%
	E2	0.02%	0.05%	3.49%	4.90%
	E3	0.02%	0.05%	6.13%	7.47%
	Average ± SD	0.02 ± 0.00%	0.05 ± 0.01%	5.01 ± 1.36%	6.63 ± 1.82%
S2	E1	0.07%	0.13%	11.05%	15.06%
	E2	0.06%	0.14%	6.99%	10.76%
	E3	0.04%	0.10%	8.06%	9.4%
	Average ± SD	0.06 ± 0.02%	0.12 ± 0.02%	8.70 ± 2.10%	11.74 ± 2.95%

The cost of shore power systems includes equipment, installation, operation, and maintenance costs. Most of these costs will be transferred to the owners of the ships at berth. This makes shore power unattractive for ship owners. Tseng and Pilcher (2015) estimated that the annual cost for a shore power terminal at the Port of Kaohsiung would be ~7000 US dollars higher per ship than a conventional terminal, whereby ships use their auxiliary engine. However, this difference is expected to decrease gradually in the long term since some costs will not be recurring. Governments can also offer incentives for adopting shore power, lowering the cost burden to the ship owners. The power companies should also have sufficient capacity to supply electricity for these systems.

The appropriate regulations governing the implementation and use of shore power also need to be addressed. Governments alongside other stakeholders will play a crucial role in the adoption of shore power systems in ports. Port authorities should comply with international standards on shore power systems to enforce regulations effectively. There are already a series of international standards on shore power compliance for ports, including high-voltage shore connection systems (IEC/ISO/IEEE 80005-1:2019) and plugs, socket-outlets, and couplers for the connection systems (IEC 62613-2:2018). These provide a clear direction on adopting shore power systems. That said, shore power offers an opportunity to improve air quality in port cities and protect human health and the environment.

4 CONCLUSIONS

The study investigated the air pollution reduction benefit of adopting shore power at the Port of Kaohsiung. NO_x, SO₂, PM₁₀, and PM_{2.5} emissions from auxiliary engines were estimated based on 2019 data, and the AERMOD dispersion model was used to simulate the dispersion of these pollutants to the city. SO₂ and NO_x were the main pollutants released from the ship emissions, with annual estimations of 345 tons and 238 tons from using HFO, and 63.9 tons and 224 tons from using MGO, respectively. The emissions were found to disperse to the city and had a maximum NO_x concentration (147 µg m⁻³) exceeding the Taiwan EPA air quality standards (100 µg m⁻³). However, SO₂ has also been considered a potential pollutant with the increase of ship calls. The average reduction benefits for NO_x and SO₂ in scenario S2 were 8.70% ± 2.10% and 11.74% ± 2.95%, respectively. Therefore, shore power significantly improves the air quality in Kaohsiung City, especially in residential areas (as high as 11.05% and 15.06% for NO_x and SO₂, respectively). However, the adoption of shore power encounters several obstacles. High cost stands to be the biggest constraint that hinders the willingness to invest and use shore power. Additionally, ports need to comply with international standards to ensure universal compatibility and safety for the systems. These constraints can be overcome by the willingness of the government and stakeholders to work together in the implementation and operation of shore power systems.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.4209/aaqr.210100>

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