Synergistic Emission Reduction of SO$_2$ and CO$_2$ Based on Clean Energy Replacement in ports

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Abstract. China's energy-saving emission reduction policy calls for improved air quality while reducing greenhouse gas emissions. This paper takes the container terminal as the research object, the energy saving and emission reduction of clean energy alternative fuels such as solar energy, wind energy, geothermal energy, LNG and electricity are studied through the combination of energy substitution and emission factors. In particular, SO$_2$ and CO$_2$ Synergistic mitigation effect. The results show that the reduction SO$_2$ and CO$_2$ is positively correlated with the usage of clean energy amount. Among them, LNG has the greatest contribution to the coordinated emission reduction of SO$_2$, and solar energy contributes the most to CO$_2$ reduction. Our conclusion is that the use of LNG and shore power in ports can achieve better synergistic emission reductions for SO$_2$ and CO$_2$. And through the use of air sources, solar energy, wind energy and light energy, CO$_2$ emission reduction effect is better than SO$_2$ emission reduction. The Chinese government can use this method as a policy tool for energy conservation and emission reduction, and vigorously promoted the application of LNG and shore power in ports.

1. Introduction
There are many important ports in China. After the 20th century, China's economy has been in a high-speed development stage, at the same time, the scale of port production increased rapidly. Port cargo throughput in 2015 increased by 3.2 times to 93.48 billion tons on 22.07 billion tons in 2000. With the port construction and production scale continues to increase, the port energy consumption pressure is also increasingly prominent. The Chinese government has issued a new ambient air quality standard and issued a new carbon emission reduction task. These measures require the reduction of greenhouse gases (GHG) emissions by regulating energy consumption while improving air quality in the port area.

Ministry of Transport of the People's Republic of China in June 2014 issued 'on the promotion of port transformation and upgrading of the views of guidance' [1]. This paper puts forward the main task of optimizing the utilization of port energy and encouraging the application of liquid natural gas, wind energy and solar energy in port enterprises to improve the proportion of clean energy and renewable energy in ports. As a way to promote the port transformation and upgrading and realize the sustainable development of terminals, particularly container terminals as the main practitioners.

China's agencies have carried out the following aspects of the study: the transport sector air pollutant emissions[2] [3], forecasting and cutting, energy planning, environmental performance assessment [4], energy use and air pollution correlation analysis [5] [6], Beijing energy conservation and carbon reduction [7], and so on. In these studies, suggestions were made on optimizing the energy consumption structure and improving the quality of the air. However, for the port energy consumption, atmospheric environment improvement and greenhouse gas emission reduction of the comprehensive...
study is relatively small. This paper takes the container terminal as an example, uses the energy substitution method and the emission factor method to analyze the SO$_2$ and CO$_2$ emission reduction effect after using the clean energy alternative fuel in the 2013-2015 period. We hope that this study can provide a reference for the port to promote the use of clean energy.

2. Analysis method

2.1. energy use compare method.
It is the comparison of energy consumption and pollutant emissions before and after cleaning alternative fuel or on-shored power.

2.2. standard coal equivalent coefficient method.
The standard coal equivalent coefficient method is used to convert the physical quantity of energy by standard coal equivalent. It is easy to compare energy consumption. Standard coal equivalent coefficient is illustrated in Table 1.

| Energy Source       | tce $^a$ | (t) | 3.15 | 1.862 | 29.3 |
|---------------------|----------|-----|------|-------|------|
| Diesel(t)           | 1.4571   | 1.4714 | 3.15 | 1.862 | 29.3 |
| Gasoline(t)         |          |      |      |       |      |
| Electricity(10,000kWh $^b$) | 3.15 | 1.862 | 29.3 |
| LNG (t)             | 1.862    | 1.862 |      |       |      |
| Solar energy (MkJ)  | 29.3     | 29.3  |      |       |      |

$^a$ tce (ton of standard coal equivalent) is 1 ton of standard coal equivalent. It is conversion target based on the calorific value of standard coal to calculate the conversion of various energy.

$^b$10,000kWh = 3.15tce, 3.15tce is average calorific value of coal consumption of 10,000 kWh electricity in China's 2015.

2.3. Emission factor calculation method.
Emission factor calculation method is used to calculate emissions of CO$_2$ and SO$_2$ after using fossil energy. Emissions of CO$_2$ and SO$_2$ are illustrated in equation (1).

$$E_{CO_2, SO_2} = EC \times EF$$

$E_{CO_2, SO_2}$ is emission of CO$_2$ (t) or SO$_2$ (kg), $EC$ is energy consumption (t, kWh), $EF$ is emission factor of CO$_2$ (t/t, t/kWh) or SO$_2$ (kg/t, kg/kWh). $E_{CO_2, SO_2}$, $EC$, $EF$ are illustrated in Table 2.

| Energy Source       | EF$_{CO_2}$ (t) | EF$_{SO_2}$ (kg) |
|---------------------|-----------------|-----------------|
| Diesel(t)           | 3.1605          | 0.7             |
| Gasoline(t)         | 2.9848          | 0.3             |
| LNG (t)             | 2.8376          | —               |
| Electricity(kWh)    | 0.0008          | 0.0028          |

$^a$LNG is shorthand of liquefied natural gas.

3. Analysis of Synergistic Emission Reduction of SO$_2$ and CO$_2$
"Synergistic emission reduction" refers to reducing greenhouse gas emissions while reducing local air pollutants[10]. Using Ningbo port Co. Ltd. Beilun second container terminal branch (NBSCT) as an example, this paper analyzes the synergistic emission reduction of SO$_2$ and CO$_2$ in greenhouse gas before and after the application of clean energy.

3.1. Terminal background
The terminal is one of the best container terminals for super-sized container ships over 10,000 twenty-feet equivalent unit (TEU) capacities. It is one of the most advanced terminal in energy saving.
and emissions reduction in China. It is the first container terminal company to power tire cranes with electricity instead of diesel fuel. It is also one of the first companies in the country to spread the use of LNG container trucks. The terminal was first evaluated as one of the 'China green port' in 2016. It has used solar energy, wind energy, geothermal energy, LNG, on-shored electricity, it is the most advanced company in application of green energy, energy-saving emission reduction effect is significant.

3.2. Analysis of the energy saving and emission reduction

In NBSCT, the use of clean energy can be summarized as three aspects. First, the application of renewable energy, ground source heat pump and solar water heater alternative fuel or coal-fired boiler heating, wind and solar lighting and other alternative shore electricity, reduce energy consumption and pollutant emissions. Second, the application of LNG, mainly to replace the level of transport vehicles fuel, reduce pollutant emissions. Third, the application of shore power, mainly to replace diesel generator power generation, reduce fuel and pollutant emissions. The following is the result.

3.2.1. Air Source Heat Pumps. Currently, NBSCT has installed 5 air source heat pumps in the replacement of oil boilers to provide 35 tons hot water for the staff canteen and shower rooms each day, fuel oil was totally replaced[11]. As a result, it used 8.1 10,000 kWh electricity to replace 281.83 ton fuel oil, saving energy 377.92 tce, and reduced 823.73 ton CO$_2$ and 0.20 ton SO$_2$.

3.2.2. Solar Water Heater. NBSCT replaced oil boilers with solar heaters in staff laundries, the solar collection area of which was 5.62 m$^2$[11]. As a result, in 2015, NBSCT consumed 407.47 MkJ hot energy, replaced 20.25 ton fuel oil, saving 13.9 tce energy, and reduced 1296 ton CO$_2$ and 0.13 ton SO$_2$.

3.2.3. Wind and Light Hybrid Street Lights. NBSCT installed 8 wind and light hybrid street lights, saving 4380 kWh of electricity annually[11], saving 1.38 tce energy, and reduced 3.51 ton CO$_2$ and 0.01 ton SO$_2$.

3.2.4. Use of LNG. Currently, NBSCT has a total of 130 horizontal transport container trucks, including 110 LNG container trucks, accounted of 84.6%[11]. In 2015, NBSCT consumed 2628.9 ton LNG, replaced 2542.65 ton diesel, increasing energy consumption 1190 tce, reducing 576.28 ton CO$_2$ and 17.80 ton SO$_2$. According to China's current calculation method, container trucks using LNG will increase the energy consumption more 32% than that of diesel.

3.2.5. Shore power. NBSCT has installed shore power facilities supplied with low voltage and normal frequency electricity, mainly used for feeder vessels for domestic trade the power of whose auxiliary engines is no more than 120 kW[11]. In 2015, 343 ships stopped at the port, consuming 39600 kWh, replacing 11.87 ton diesel, saving 12.47 tce energy, and reduced 4.97 ton CO$_2$ and 0.50 ton SO$_2$.

The effect of energy conservation and emissions reduction results from using shore power for ocean going vessels at berth instead of power generated by auxiliary engines on board has a close relationship with level of power generation and power source. NBSCT 's electricity comes from thermal power, electricity is coal-fired electricity which is regarded as dirty electricity. However, in order to improve air quality, the Chinese government has called for ultra-low emissions of power plants[12], Which means that thermal power plants need to use a variety of pollutants efficient synergistic emission reduction technology, so that the concentration of air pollutants in line with air pollutant emission limits, Dust, sulfur dioxide, nitrogen oxide emission concentration (baseline oxygen content of 6%) were not more than 10 mg / m$^3$, 35 mg / m$^3$, 50 mg / m$^3$. According to the data provided by the China Electricity Council, energy resource consumed per unit electricity generated by 6MW and above power plants in China is 315 gce/kWh in 2015, according to 2012 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships issued by the International Maritime Organization (IMO)[13],fuel consumption rate of
power generation for auxiliary engine of ocean going vessels is 300 g/kWh. We calculated the reduction of pollutants by shore electricity instead of ship auxiliary power generation. The results show that using shore power for ocean going vessels at berth instead of power generated by auxiliary engines on board in China can save energy while reducing carbon dioxide and sulfur dioxide emissions, the results are shown in Table 3.

Table 3. Effect of application of shore power for ocean going vessels at berth in China.

| Energy consumption | CO₂ [g/kWh] | SO₂ [g/kWh] |
|--------------------|-------------|-------------|
| Generated by auxiliary engines on board | 428.4       | 934.9       | 15.49 |
| Shore power        | 315         | 801.86      | 2.86  |
| Emission reduction | -113.4      | -133.02     | -12.63 |

By the application of above clean energy, including air source heat pumps, solar water heater, wind and light hybrid street lights, shore power, NBSCT reduced the energy consumption significantly, reduced much CO₂ and SO₂. And the use of LNG container trucks will increase energy consumption, but it will significantly reduce CO₂ and SO₂. The results are shown in table 4.

Table 4. The reduction of energy consumption, CO₂ and SO₂.

| Energy Reduction (tce) | Air Source | Solar Energy | LNG | Shore Power | Wind and Light Energy |
|------------------------|------------|--------------|-----|-------------|-----------------------|
| CO₂ Reduction (t)      | 377.92     | 13.90        | -1190 | 12.47 | 29.3 |
| SO₂ Reduction (t)      | 889.30     | 1296.00      | 576.28 | 5.27  | 3.51 |

3.3. Analysis of Clean Energy Contribution of Synergistic Emission Reduction

Assuming that L represents a certain gas (CO₂ or SO₂), \( r_{i,L} \) represents the proportion of total emission reductions after the use of clean energy to the total emission reduction rate. We analyze and select clean energy that can reduce both CO₂ and SO₂ emissions. The formula is as following.

\[
r_{i,L} = \frac{\Delta R_{i,L}}{\Delta R_L}
\]

\( r_{i,L} \) is defined as the contribution rate of clean energy to synergistic reductions, \% \( \Delta R_{i,L} \) is the relative emission reduction of the clean energy i after the application of the gas L ((CO₂ or SO₂), \( \Delta R_L \) is the total emission reduction of gas L after cleaning energy applications.

The relative emission reductions and total emission reductions of CO₂ or SO₂ are shown in Table 3.

Table 5. Synergistic Emission Reduction contribution rate %.

| CO₂ | Air Source | Solar Energy | LNG | Shore Power | Wind and Light Energy |
|-----|------------|--------------|-----|-------------|-----------------------|
| 32.10 | 46.79     | 20.80        | 0.19 | 0.13        |
| 0.17 | 0.76      | 95.49        | 2.68 | 0.07        |

The results show that LNG has the greatest contribution to SO₂, and the contribution rate is 95.49% in 2015. The second is the shore power, air source, solar energy, wind energy and light energy, the contribution rate is 2.68%, 1.17%, 0.76%. The contribution rate of air energy, LNG, shore power, wind energy and light energy to CO₂ in 2015 is 32.10%, 20.80%, 0.19% and 0.13% respectively. The contribution rate of solar energy to CO₂ is the largest and the contribution rate is 46.79%. In contrast, wind energy and light energy contribute the least to synergistic reductions, mainly because wind and
light can be used for outdoor lighting in ports, and the proportion of electricity consumption is relatively small, so the effect of emission reduction is relatively insignificant.

3.4. Factor Analysis of Cooperative Emission Reduction

On the basis of the above analysis, in order to further evaluate the synergistic effect of SO$_2$ and CO$_2$ emission reductions of various clean energy sources, this paper calculates the synergistic coefficients $k_{i,L}$ of SO$_2$ relative to CO$_2$ emission reduction. The formula is shown in (3).

$$k_{i,L} = \frac{r_{i,SO_2}}{r_{i,CO_2}}$$

(3)

$r_{i,SO_2}$ and $r_{i,CO_2}$ is the synergistic emission reduction contribution rate of SO$_2$ and CO$_2$ for clean energy i, as shown in Table 3. If $k_{i,L} = 1$, it indicates that the factor SO$_2$ and CO$_2$ are in a higher degree of co-ordination. If 0 < $k_{i,L}$ < 1, it indicates that the factor SO$_2$ is lower than the CO$_2$ emission reduction level. If $k_{i,L}$ > 1, higher than CO$_2$ reduction. Calculation results of $k_{i,L}$ are shown in Table 6.

| Air Source | Solar Energy | LNG | Shore Power | Wind and Light |
|------------|-------------|-----|-------------|----------------|
| $k_{SO_2/CO_2}$ | 0.0364 | 0.0149 | 4.5907 | 14.1010 | 0.4234 |

By calculating and analyzing SO$_2$ and CO$_2$ emission reduction synergistic coefficients, it can be seen that LNG trucks and shore power are relatively large in terms of port energy use, so they are relatively large in fuel substitution. With the improvement of energy consumption and energy efficiency in ports, $k_{SO_2/CO_2}$ is greater than 1, SO$_2$ and CO$_2$ can achieve a higher degree of mitigation, SO$_2$ emission reduction is greater than the degree of CO$_2$ emission reduction. Air source, solar energy, wind energy and light energy $k_{SO_2/CO_2}$ less than 1, indicating that the degree of emission reduction of CO$_2$ is greater than the degree of emission reduction of SO$_2$.

4. Application Prospect of Clean Energy in Port

Due to the use of clean energy technologies facing increased costs and energy security and other issues, only the scale of production in the forefront of the industry, environmental pressure on the port terminals gradually began to demonstrate the application, such as Shenzhen Yantian Port, Ningbo Zhoushan Port, Shanghai Port, Qingdao Port, etc. It has not yet been widely used in Chinese ports. According to the port's energy consumption structure, usually the production operations accounted for more than 98% of total energy consumption, auxiliary production operations accounted for about 2%. Solar energy, geothermal energy, wind energy and light energy and other renewable energy sources are usually used in the auxiliary production operations, energy-saving emission reduction effect is limited, but in the production operations, you can use LNG and electricity to replace fuel, energy-saving emission reduction effect is obvious. This is consistent with the conclusion of this paper. As a result, both theory and practice have proven that energy use is promoted at the port to promote clean energy while reducing SO$_2$ and CO$_2$ emissions.

During the 12th five-year period, the Ministry of Transport of the People's Republic of China issued a series of relevant documents, in order to guide the port to use LNG and shore electricity, to promote the port to optimize the energy structure, to achieve energy-saving emission reduction targets.

Such as the 'arrangement of work for energy conservation and emission reduction for waterway transport sector during the national 12th Five-Year plan' [14], there are two major jobs mentioned, one is applications of LNG driven transport vehicle technology, the other is to promote the use of shore power technology in container ships and bulk carriers. Since 2011, supporting by the Special Fund for Energy Conservation and Emissions Reduction for Transport Sector, China Ministry of Transport gave awards to terminals which construct facilities for supplying shore power for ocean going vessels at
berth, and China shipping companies which add facilities on board in their vessels to receive shore power. Port of Lianyungang, Port of Shenzhen and Hebei ocean shipping group Co. Ltd. received more than 10 million RMB in total. Since 2014, China's Ministry of Transport announced two batches of LNG pilot and demonstration projects for water transport applications, Port of Lianyungang, Port of Shenzhen and Port of Ningbo won the first batch of demonstration project of LNG container truck. Therefore, on the one hand is the actual needs of energy-saving and emission reduction, on the other hand is the government policy support, both aspects are conducive to promoting the use of clean energy in ports.

5. Conclusions
Through the above analysis, we can draw the following conclusions.
First, the results show that the reduction \(\text{SO}_2\) and \(\text{CO}_2\) is positively correlated with the usage of clean energy amount. Among them, LNG has the greatest contribution to the coordinated emission reduction of \(\text{SO}_2\), and solar energy contributes the most to \(\text{CO}_2\) reduction. Wind energy and light energy in the clean energy alternative to the smallest proportion, so its contribution to the smallest reduction.
Second, the use of LNG and shore power in ports can achieve better synergistic emission reductions \(\text{SO}_2\) and \(\text{CO}_2\). And through the use of air sources, solar energy, wind energy and light energy, \(\text{CO}_2\) emission reduction effect is better than \(\text{SO}_2\) emission reduction.
Finally, By the promotion of LNG and shore electricity in ports, We can bring significant effect of air pollutant emission reduction and greenhouse gas emission reduction. Therefore, this paper suggests that the transportation authorities can use this method as a policy selection tool for energy conservation and emission reduction.

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