

Analysis of Environmental Benefits of Shore Power for Preventing and Controlling Air Pollution Caused by Vessels at Berth

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Abstract. When vessels are berthed at ports, the air pollutants emitted by auxiliary engines will cause severe pollution to the ports and surrounding environments. In view of this situation, the author first summarizes the Chinese policies and policies of foreign countries on emission of air pollutants from vessels at berth, and then analyses the current status of and measures for control of air pollutant emission from vessels at berth. Secondly, the author analyses the environmental benefits of using shore power for better controlling air pollutant emission from vessels at berth, compares vessels using shore power with vessels using generated power in the energy conservation and emission reduction effects based on the fuel consumption rate of different auxiliary engines and current status of pollutant emission from power generation in China etc., analyses the current status of shore power application in China, estimates the energy conserved and emission reduced when shore power is used by vessels at berth. Thirdly, the author identifies the scale of electric energy replacement by, and environmental benefits of, shore power at ports in China. This paper delivers innovative approaches to the comparison between the effects of energy conservation and emission reduction based on fuel consumption rates of different auxiliary engines and estimation of conserved energy and reduced emission.

1 Introduction

When auxiliary engines are used to supply power to the equipment onboard vessels berthed at ports, the pollutants emitted by auxiliary engines will cause severe pollution to the ports and surrounding environments. Policies have been enacted both in China and foreign countries to restrict the emission of air pollutants from vessels at berth. Such policies mainly include MARPOL Annex VI^[1], which requires to reduce the sulfur content in marine fuels to 1.0% m/m from January 1st 2010 onwards and to 0.1% m/m from January 1st 2015 onwards within the emission control areas in the Baltic Sea and the North Sea; EU Directive 2005/33/EC, which responds to the requirements of MARPOL Annex VI for the sulfur content in marine fuels used in EU countries and sets more stringent requirements, i.e. fuels with sulfur content above 0.1% m/m shall not be used for vessels that are berthed at the ports of EU member countries for more than two hours from January 1st 2010 onwards; *Airborne Toxic Control Measure for Auxiliary Diesel Engines Operated on Ocean-Going Vessels At-Berth* in a California Port (At-Berth Regulation)^[2], which requires that from January 1st 2017 onwards, the number of vessels of large shipping companies and shipping companies requiring frequent berthing using shore power upon arrival at ports must account for 70%

of the total number of vessels at port and alternative means shall meet the requirement of reducing the emission of pollutants by at least 70%, this code directly requires the vessels at berth to use shore power or alternative control techniques and is more stringent than MARPOL Annex VI and EU Directive; *Implement Plan on Domestic Emission Control Areas in Waters of the Pearl River Delta, the Yangtze River Delta and Bohai Rim (Beijing, Tianjin and Hebei)* in China^[3], which stipulates that from January 1st 2017 onwards, fuels with sulfur content $\leq 0.5\%$ m/m shall be used for vessels that are berthed alongside the core port areas within the emission control areas (except the period of one hour after berthing and before departure, the same below), from January 1st 2018 onwards, fuels with sulfur content $\leq 0.5\%$ m/m shall be used for vessels that are berthed at all ports within the emission control areas, from January 1st 2019 onwards, fuels with sulfur content $\leq 0.5\%$ m/m shall be used for vessels that enter the emission control areas, and that alternative control measures with effects equivalent to the aforementioned emission control requirements, such as connection to shore power, use of clean energy and exhaust gas after-treatment.

The studies of scholars in China and foreign countries on pollutant emission from vessels at berth mainly focus on pollutant emission inventory, current status of pollutant emission and preventive/control

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measures, among which preventive measures are mainly the administrative measures to be taken by the government [4]. Among pollution prevention and control measures, shore power

technology is an environmentally friendly technology that has been developed in large scale in recent years. The related references to this technology mainly involve the application and development of shore power technology at China and foreign countries, analysis of the technical experiences in the use of shore power in foreign countries, extension of application of shore power technology in China [5-7] and analysis on the economic and environmental benefits of the use of shore power considering a certain port as the object of analysis. In additions, the fuel consumption rates applied in these references are the optimum rates of fuel consumption of auxiliary engines and the impact of actual engine load factor is not considered.

This paper analyses the current measures for preventing and controlling air pollution caused by vessels at berth, compares the energy conservation and emission reduction effects of shore power with those of self-generated power of vessels considering the different fuel consumption rate of auxiliary engines, current status

of pollutant emission from power generation in China, etc. and analyzes the environmental benefits, energy conservation and emission reduction achieved through the use of shore power at the main ports of China.

2 Analysis of the current measures for preventing and controlling air pollution caused by vessels at berth

2.1 Analysis of the measures for preventing and controlling air pollution

The current measures for preventing and controlling air pollution caused by vessels at berth are summarized in Table 1. Among the energy conserving and emission reducing measures applicable to vessels at berth, the use of low sulfur fuel and shore power is an emission reducing measure applicable to most vessels. Shore power is a source of power supply that can prevent and control pollution and is used to supply power to vessels berthed at ports when the auxiliary engines on-board the vessels are shut down.

Table 1. Measures for Preventing and Controlling Air Pollution Caused by Vessels at Berth

No.	Type of measure	Measure	Description
1	Use of clean energy in place of fuel	Use of shore power	Shore power is used by vessels at berth and no pollutant is emitted in the port location.
2		Use of liquefied natural gas	Only applicable to liquefied natural gas carriers or powered vessels. Carbon dioxide emission is approximately 430 g/kWh; oxides of nitrogen (NOx) emission is approximately 1.4 g/kWh.
3		Use of battery power	Only applicable to vessels that are berthed at port for a short time and consume limited electric power, such as automobile transport vessel.
4	Improvement of fuel quality	Use of low sulfur fuel	According to the requirements of emission control areas at the moment, marine fuels with lower sulfur content than the fuels being used by vessels mainly refer to marine fuels with 0.5% or 0.1% sulfur content. See Table 2.
5		Use of emulsified diesel	Emulsified diesel is produced by mixing water with biodiesel and emulsifying the mixture with emulsifier and assistant emulsifier and is used for auxiliary generators. Particulate emission reduced by 57%, nitrogen oxides emission reduced by 8%-10% and carbon dioxide emission reduced by 12.6%.
6	New technology for energy conservation and emission reduction	Gas hood	When vessels are berthed, closed gas hood is mounted onto the exhaust stack to collect the flue gas emitted by the auxiliary engines for discharge after purification. Particulate emission reduced by 98% and nitrogen oxides emission reduced by 95%.
7		Flue gas scrubbing system	Seawater flue gas scrubbing system is mounted onto the exhaust stack of the vessel to purify the gases emitted.
8		Oil-electricity mixed power tug	The tug is equipped with diesel-electricity mixed power generator. Fuel energy saved by 20%-30%, particulate matter (PM) emission reduced by 44% and oxides of nitrogen emission reduced by 44%.
9		Selective catalytic reduction (SCR)	Under the action of the catalyst, the NOx in the exhaust gas from the engine is reduced to N2 and H2O.

Ocean-going vessels mainly use marine fuel. Sulfur content is the main characteristic parameter of marine fuel quality. Marine fuel with higher sulfur content will generate more pollutants (nitrogen oxides, inhalable particulates, etc.) when used. Table 2 illustrates the emission factors of various gases emitted by auxiliary generators described in the At-Berth Regulation [2]. In the Table 2, it can be seen that the use of low sulfur fuel by vessels reduces the emission of sulfides (SO_x) but does not eliminate the emission of inhalable particulates matter (PM₁₀) and fine particulate matter (PM_{2.5}), and hardly reduces the emission of oxides of nitrogen (NO_x), methane (CH₄) and carbon monoxide (CO).

According to EU's researches, it is believed that the most economic way to reduce pollutant emission from vessels at berth is to stop using auxiliary engines and connect to shore power at the port. Shore power technology reduces the mission of all air pollutants;

noise and vibration of vessels berthed at port and complies with the requirements of MARPOL Annex VI. Therefore, through the use of shore power by vessels at berth, the emission of air pollutants from auxiliary engines can be completely eliminated at port and transferred to the area where the power plant is located.

Table 2. Auxiliary engine emissions factors with different sulfur content

Fuel type	NO _x	SO _x	CO ₂	CH ₄	CO	PM ₁₀	PM _{2.5}
MDO (0.1% S)	13.9	0.4	690	0.09	1.1	0.25	0.23
MDO (0.5% S)	13.9	2.1	690	0.09	1.1	0.38	0.35
HFO	14.7	11.1	722	0.09	1.1	1.5	1.46

2.2 Current status of shore power application in China

Survey data indicates that as of February 2018, there were 859 completed shore power stations (of 200 kVA and above) at ports with a throughput above the specified level main ports in China, including 198 high-voltage (HV) stations and 661 low voltage (LV) stations, among which 229 stations were constructed for container berths, Ro/Ro Passenger berths, cruise berths, passenger berths above 3000 ton capacity and bulk berths above 50,000 ton capacity and 182 stations were included in the Shore Power Station Layout Plan for Ports, accounting for 36.92% of the total number of berths planned. Currently, there is still a big gap between the number of shore power stations constructed in ports and the target number of shore power stations to be completed by 2020 to cover 50% berths at the container berths, Ro/Ro Passenger berths and cruise berths in the main ports in China.

In addition, the power receiving systems of 358 vessels (of 3000 ton and above) have been constructed modified. 262 power receiving systems have been constructed for power supply to container vessels, dry bulk vessels and ordinary passenger vessels, and this number accounts for a low percentage of the total number of power receiving systems to be constructed as planned, i.e. 0.23%.

3 Comparison between the energy conservation and emission reduction effects of shore power and those of self-generated power onboard vessels

3.1 Fuel consumption rate of marine auxiliary engines

The rated fuel consumption rate of marine auxiliary engines is generally within the range of 200 g/kWh~230 g/kWh and is normally taken as 210 g/kWh by IMO for calculating the design energy efficiency index of vessels. When vessels are berthed, the auxiliary engines will operate under partial load. The auxiliary engines load factors when different vessels are berthed are given in Table 3 [2].

Fuel consumption rate varies greatly with the auxiliary engines load factor for vessels at berth. Fig. 1 shows the results of monitored fuel consumption of two operating auxiliary engines and the fuel consumption rate is within the range of 150 g/kWh~450 g/kWh and the lowest fuel consumption rate corresponds to 3/4 operating load. The fuel consumption rate is 200 g/kWh when the auxiliary engines are operating under full load, which is close to value provided by the manufacturer. From Fig. 1, it can be seen that fuel consumption rate varies greatly with load factor [9].

In this research, three values have been taken for comparison through comprehensive analysis and these

three values are respectively 215 g/kWh, a fuel consumption rate commonly used in existing references, 235 g/kWh, a relatively low fuel consumption rate, and 360 g/kWh, a fuel consumption rate determined in the Shore Power Subsidy Calculation Method issued by Shenzhen City taking into account various factors.

Table 3. Auxiliary power and load factor of different types of vessels

Vessel type	Average Main Engine Power (kW)	Average Auxiliary Power (kW)	Hotelling Load Factor
Bulk Carrier	8,000	1,776	22%
Container vessel	30,900	6,800	17%
Passenger vessel	39,600	11,000	64%
General Cargo	9,300	1,776	22%
Miscellaneous	6,250	1,680	22%
RORO	11,000	2,850	30%
Reefer	9,600	3,900	34%
Tanker	9,400	1,985	67%

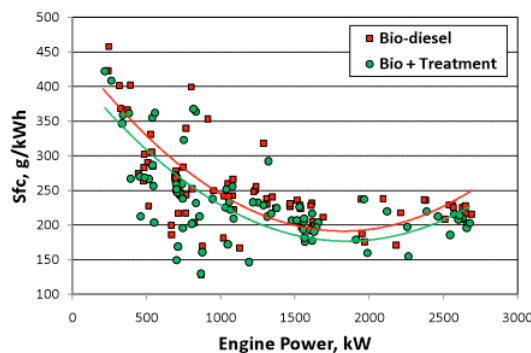


Fig.1 Fuel consumption rate of vessels under different load factor

3.2 Comparative analysis of energy conservation and emission reduction effects

The electric power data in 2016 have been taken for comparative analysis of energy conservation and emission reduction effects.

According to the data included in the Report on Development of Clean Coal-based Power in China-China Electricity Council, in 2016, the standard coal consumption for power supply was 312 g/kWh, sulfur dioxide emission factor for power supply was 0.39 g/kWh, nitrogen oxide emission factor for power supply was 0.36 g/kWh, particulate emission factor for power supply was 0.08g/kWh, and hydropower, nuclear power, grid-connected wind power and solar energy accounted for 34.5% of gross power generation.

For the energy conservation and emission reduction effects of the use of shore power in place of power generated by auxiliary engines for vessels at berth, see Table 4. The emission factors for various pollutants emitted during power generation by auxiliary engines are calculated according to the MDO (0.5%S) data given in Table 2.

From Table 4, it can be seen that:

Table 4. Effect of energy saving and emission reduction using shore power (compared with 0.5%S fuel ratio)

Comparison project		Energy consumption	Greenhouse gas emissions	Emission of air pollutant		
		Standard coal,gce/kWh	CO ₂ , g/kWh	SO ₂ , g/kWh	NO _x , g/kWh	PM, g/kWh
①	Auxiliary engines (215)	307.1	690	2.1	13.9	0.35
②	Auxiliary engines (235)	335.6				
③	Auxiliary engines (360)	514.2				
④	Shore power (All thermal power)	312	822	0.39	0.36	0.08
⑤	Shore power (65.5% thermal power)	<312	538.41			
⑥	Effect comparison	-202.2~+4.9	-151.59~+132	-1.71	-13.54	-0.27
⑦	Reduction rate	-39%~+1.6%	-22%~+19.1%	-81.43%	-97.41%	-77.14%

Notes: 1) The characters in brackets behind the auxiliary engines are fuel consumption rates, expressed in g/kWh. The two typical values (235g/kWh and 360g/kWh) in this table are selected, A lower numerical value (215g/kWh) used in the coastal electricity literature is also selected for comparison.
 2) The effect comparison is made between shore power and auxiliary engines data at different fuel consumption rates. Minimum value is ④-③, Maximum value is ④-①; The reduction rate is the reduction ratio of shore power to auxiliary engines. Minimum value is (④-③) / ③, Minimum value is (④-①) / ①.

(1) The use of shore power can significantly reduce the emission of air pollutants (SO₂, NO_x, PM, etc.). In addition, as power plants may be equipped with process facilities such as those for centralized desulfurization, the actual level of air pollution emission will be even lower.

(2) Auxiliary engines equipped onboard vessels tend to cause noise pollution and the A-weighted sound level of noise at the location of auxiliary engines operation in the manned machinery space may reach approximately 90 dB(A), affecting the normal work and rest of personnel onboard. After shore power is connected, the noise pollution caused by the auxiliary engines onboard vessels at berth will be eliminated.

(3) The energy conservation effects of the use of shore power depend on the fuel consumption rate of auxiliary engines and the source of shore power. When the fuel consumption rate is 215 g/kWh, the use of shore power does not save energy, but when the fuel consumption rate is higher than 235 g/kWh, the use of shore power saves energy. As the fuel consumption rate of auxiliary engines used for power generation is related to the power and load factor of the auxiliary engine, 215 g/kWh is a relatively low rate under optimum operating conditions. When vessels are berthed, the auxiliary engine will operate under partial load, under such conditions, the power of the auxiliary engine will normally be 20%~35% of its rated power and the fuel consumption rate of the auxiliary engine will normally be higher than the rated fuel consumption rate. For these reasons, the actual fuel consumption rate of operating auxiliary engines may be much higher than this value. For example, in the Shore Power Subsidy Calculation Method issued by Shenzhen City, the fuel consumption rate is set to 360 g/kWh taking into account various factors. In addition, the consumption of thermal power among the sources of shore power decreases year by year, which is favourable for improving the energy conservation effects of the use of shore power. Therefore, in most cases, the technology of shore power is energy-conserving.

(4) The possibility of reducing greenhouse gas emission by using shore power depends on the proportion of thermal power used. If thermal power is used as the unique source of shore power, the use of

shore power does not reduce greenhouse gas emission. The power supply in China is now developing with a trend of reduced thermal power proportion and increased proportion of electric power generated from clean energy. For example, the proportion of thermal power decreased to 65.5% and the proportion of power generated from clean energy increased to 34.5% in 2016. Under such circumstances, the use of shore power can significantly reduce the emission of greenhouse gas (CO₂).

In summary, the use of shore power by vessels at berth is a technical measure that can save energy and reduce carbon emission, emission of pollutants and noise under current circumstances.

4 Estimation of energy conserved and emission reduced by use of shore power

The electric power replacement by shore power is calculated based on berth utilization rate. The vessel berthing time is taken as the annual total time multiplied by berth utilization rate, and the vessel to shore power connection time is obtained by deducting vessel auxiliary operation time from vessel berthing time. The formula for calculation is as follows:

$$E = \sum_{i=0}^n 0.9T_i \cdot P_i \cdot Q_i \tag{1}$$

where,

E denotes the cumulative electric power replacement throughout the year, expressed in kWh;

T_i denotes the annual total time of the i^{th} berth, expressed in h;

P_i denotes the berth utilization rate of the i^{th} berth;

Q_i denotes the average electric load of the vessel at the i^{th} berth.

According to the *Statistical Bulletin on Transport Industry Development in 2016* issued by the Ministry of Transport [10], as of the end of 2016, there were 30388 berths at terminals used for production in the ports of China, including 5887 berths at terminals used for production in coastal ports and 24501 berths at terminals used for production in inland waterway ports, and there were 2317 berths with a capacity of 10000 ton and above

in the ports of China, including 1894 such berths in coastal ports and 423 such berths in inland waterway ports.

According to the statistics, the berth utilization rates for coastal ports and inland waterway ports with a capacity of 10000 ton and above are 60% and 50% respectively; and the berth utilization rates for coastal ports and inland waterway ports with a capacity below 10000 ton are 50% and 40% respectively. The electric load of vessels of 10000-100000 tons at berth is calculated as 200-1000 kW, and the electric loads for coastal ports and inland waterway ports with a capacity below 10000 ton are calculated as 100 kW and 30 kW respectively.

Finally, the power consumptions of vessels at berth in inland waterway ports and of vessels at berth in coastal ports are estimated using equation (1), which are 2986.27 million kWh and 6481.68 million kWh respectively, and the total power consumption of vessels at berth in the ports of China is estimated to be 9467.95 million kWh (9.468 billion kWh). This total power consumption accounts for 9.5% of the target cumulative electric power replacement (100 billion kWh) to be achieved by 2015 mentioned in the Implementation Plan for Electric Power Replacement of the State Grid Corporation of China.

As roughly estimated according to Table 4, the annual shore power consumption will be 9.468 billion kWh and the annual fuel consumption will be reduced by 3.40 million tons if shore power is used by all vessels berthed at all terminals used for production in China, and taking into account indirect emissions from power plants, the annual SO₂, NO_x and CO₂ emissions will be reduced by 16 thousand tons, 128 thousand tons and 1435 thousand tons respectively.

5 Conclusions

(1) The regulations on the control of pollutant emission from vessels at berth in China and foreign countries have intensified, and particularly, European and American countries have presented the timetable for implementing the measures to control pollutant emission. China has also arranged emission control areas and formulated regulations on the use of fuels. In particular, *the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution* stipulates that "vessels berthed at ports shall preferably use shore power", however, it is still difficult to implement such requirements and regulations.

(2) The use of shore power by vessels at berth is one of the most effective control measures for reducing the emission of air pollutant. Comparative data-based analysis indicates that under current circumstances, the use of shore power by vessels at berth is a technical measure that can save energy, reduce carbon emission, emission of air pollutants and noise. As a competent governmental authority, the Ministry of transport is vigorously promoting the use of shore power by vessels at berth. However, as the progress of such promotion and the effects of use of shore power are still below the

expected levels, the enforcement will be strengthened continuously.

(3) As calculated assuming that shore power is used by all vessels berthed at all terminals used for production in China, the following environmental benefits will be achieved through the use of shore power by vessels at berth: the annual electric power replacement will be 9.468 billion kWh, the annual SO₂, NO_x and CO₂ emissions will be reduced by 16 thousand tons, 128 thousand tons and 1435 thousand tons respectively, the emission of air pollutants will be reduced significantly and the use of shore power by vessels at berth will become an effective means of reducing the emission of air pollutants from vessels at berth and improving the air quality in port areas.

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