Green Energy and Resources 1 (2023) 100046

Contents lists available at ScienceDirect

Green Energy and Resources

journal homepage: www.journals.elsevier.com/green-energy-and-resources

Emission reduction and cost-benefit analysis of the use of ammonia and green hydrogen as fuel for marine applications

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A R T I C L E I N F O

Keywords:
Cost-benefit analysis
Guangzhou port
Ammonia
Hydrogen
Emissions

A B S T R A C T

Increasingly stringent emission standards have led shippers and port operators to consider alternative energy sources which can reduce emissions while minimizing capital investment. It is essential to understand whether there is a certain economic investment gap for alternative energy. The present work mainly focuses on the simulation study of ships using ammonia and hydrogen fuels arriving at Guangzhou Port to investigate the emission advantages and cost-benefit analysis of ammonia and hydrogen as alternative fuels. By collecting actual data and fuel consumption emissions of ships arriving at Guangzhou Port, the present study calculated the pollutant emissions and cost of ammonia and hydrogen fuels substitution. As expected, it is shown that with the increase of NH_3 in fuel, mixed fuels will effectively reduce CO and CO_2 emissions. Compared to conventional fuel, the injection of NH_3 increases the NO_x emission. However, the cost savings of ammonia fuel for CO_2, SO_x and PM_{10} reduction are higher than that for NO_x. In terms of pollutants, ammonia is less expensive than conventional fuels when applied to the Guangzhou Port. However, the cost of fuel supply is still higher than conventional energy as ammonia has not yet formed a complete fuel supply and storage system for ships. On the other hand, hydrogen is quite expensive to store and transport, resulting in higher overall costs than ammonia and conventional fuels, even if no pollutants are produced. At present, conventional fuels still have advantage in terms of cost. With the promotion of ammonia fuel technology and application, the cost of supply will be reduced. It is predicted that by 2035 ammonia will not only have emission reduction benefits, but also will have a lower overall economic cost than conventional fuels. Hydrogen energy will need longer development and technological breakthroughs due to the limitation of storage conditions.

1. Introduction

Over the past few years, the problem of energy scarcity and emissions has become a matter of increasing concern to all sectors of society. The proportion of fossil fuels has declined with the opening of various new and sustainable energy sources but remains large in most countries. Meanwhile, with the increasing energy demand, the burning products of fossil fuels have caused many global problems, including the greenhouse effect, ozone depletion, acid rain and environmental pollution. In marine transport, heavy fuel oil is a low-quality fuel that is still used as primary energy for propulsion systems, which causes high pollutant emissions to the atmosphere (Prussi et al., 2021; Wang, 2023). Marine vessels contribute between 14% and 31% of NO_x emissions, about half of SO_x emissions and 23% of CO_2 emissions. With the globalisation of the manufacturing industry and the enhancement of global-scale trades, nearly 90% of the external freight trades are transported by marine vessels, an important sector in Europe (Monteiro et al., 2018).

In order to decrease the impact of marine transport, the International Maritime Organization (IMO) enacted the Marine Pollution Convention in 1973, with the objective to minimise pollution from marine ships and accidental pollution (Fuentes García et al., 2021). With the economic and technological development, new amendments to the Marine Pollution Convention were adopted in 2011 and came into force by 2013. The new reduction convention mainly concentrated on sulphur content in fossil fuels, and the threshold for sulphur content was 4.5% mass by mass between 2000 and 31 December 2011, 3.5% mass by mass from 2012 to 31 December 2019, and 0.5% mass by mass in the year 2020 (IMO, 2020 – cutting sulphur oxide emissions, 10 August 2020). So, the new limit on

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https://doi.org/10.1016/j.gerr.2023.100046
Received 17 July 2023; Received in revised form 6 December 2023; Accepted 7 December 2023

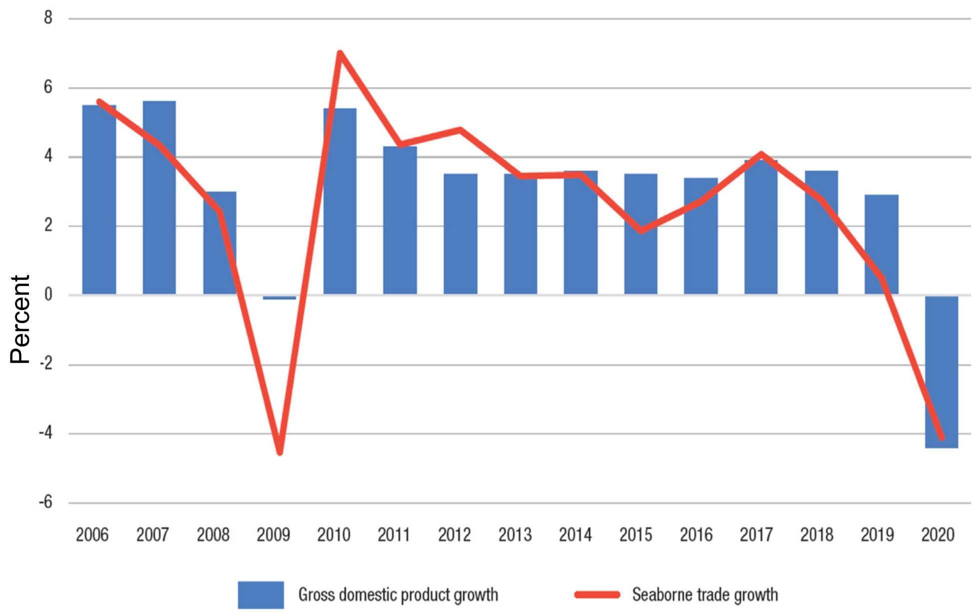

Fig. 1. International marine commerce and global output development, 2006~2020 (UN Conference on Trade and Development, 2021).

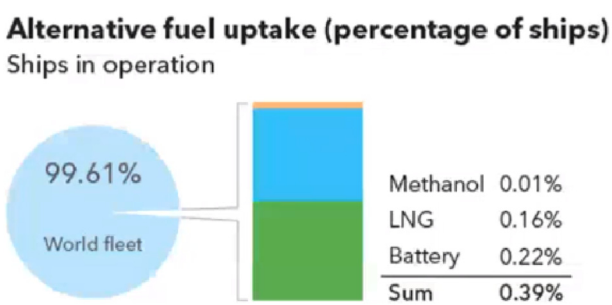

Fig. 2. The ratio of different fuels in the operation of ships (Maritime Forecast to 2050, 2021).

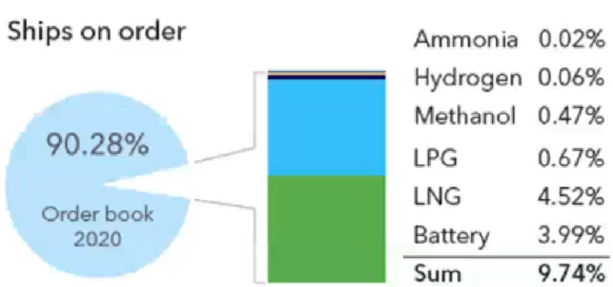

Fig. 3. The ratio of different fuels ordered for ships (Maritime Forecast to 2050, 2021).

sulphur content enacted in 2020 made a vital milestone in maritime transport to improve air quality, protect the earth's environment and improve human health. This limit includes five advantage changes from the Marine Pollution Convention in sulphur, including cleaner air, positive impacts on human health, higher-quality fuels, ship owners or operators and enforcement authorities.

More stringent conventions for ocean-going vessels are reducing the negative impact on the surrounding environment, especially in offshore ports. Some areas also have more stringent emission control; for example, the North Sea, North American, Baltic Sea and the United States Caribbean Sea achieved 0.1% mass by emission limitation on mass sulphur oxide after 2015 (IMO, 2020 – cutting sulphur oxide emissions, 10 August 2020). In addition, there are some regulations for other emissions of maritime transportation. The Energy Efficiency Design Index is usually used to mandate all ships to meet the Ship Energy Efficiency Management Plan, which stipulates the lowest energy efficiency level per capacity mile of diverse vessel types and sizes, and the Energy Efficiency Design Index will change every five years to simulate the new technological innovation.

As time goes on, the emission requirements for Marine vessels have and will become more and more stringent. Even though the shipyard is constantly improving its technology to reduce emissions, as the technological development of traditional fuels reaches its peak, the high investment cost brought by further development is different from the decreasing emission reduction. In response, the maritime sector is actively pursuing decarbonisation strategies to align with global carbon neutrality goals. This shift has increased interest in zero-emission fuels such as ammonia and hydrogen, aimed at transforming ship power sources and operation. Meanwhile, the performance of relevant combustion technologies is increasingly being investigated. For instance, fully premixed ammonia/methane/hydrogen mixtures are used effectively in tangential cyclone burners (Mashruk et al., 2022). Mild combustion of methanol and ethanol, due to its inherent properties, can significantly improve combustion stability and keep NO_x emissions at acceptable levels (Ariemma et al., 2023).

2. Literature review

So far, there are huge alternative energy sources that have been around for a while and have had some success. This part of the paper mainly introduces the research background and main characteristics of various alternative energy sources. Fig. 1 shows the change in international seaborne trade and world gross domestic product from 2006 to 2020. (UN Conference on Trade and Development, 2021). The fluctuation trends of world maritime trade growth and GDP growth are very similar. Except for the negative growth of about 4.2% caused by the impact of the financial crisis in 2008 and the epidemic in recent years, they all maintained high growth in other periods.

The Det Norske Veritas (DNV) website shows the ratio of different fuels in operation and ship orders, as shown in Figs. 2 and 3 (Maritime Forecast to 2050, 2021). In 2021, 99.5% of vessels are based on conventional fuels,

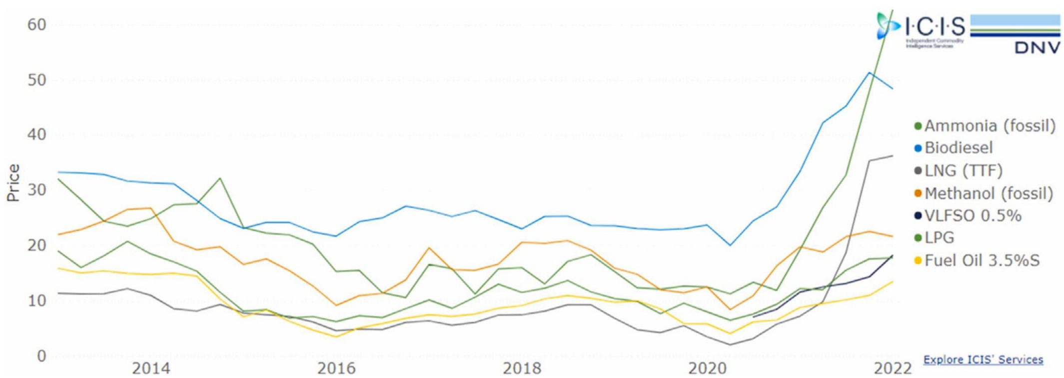

Fig. 4. The change of fuel price between 2014 and 2022 (Alternative Fuels Insight, 2023).

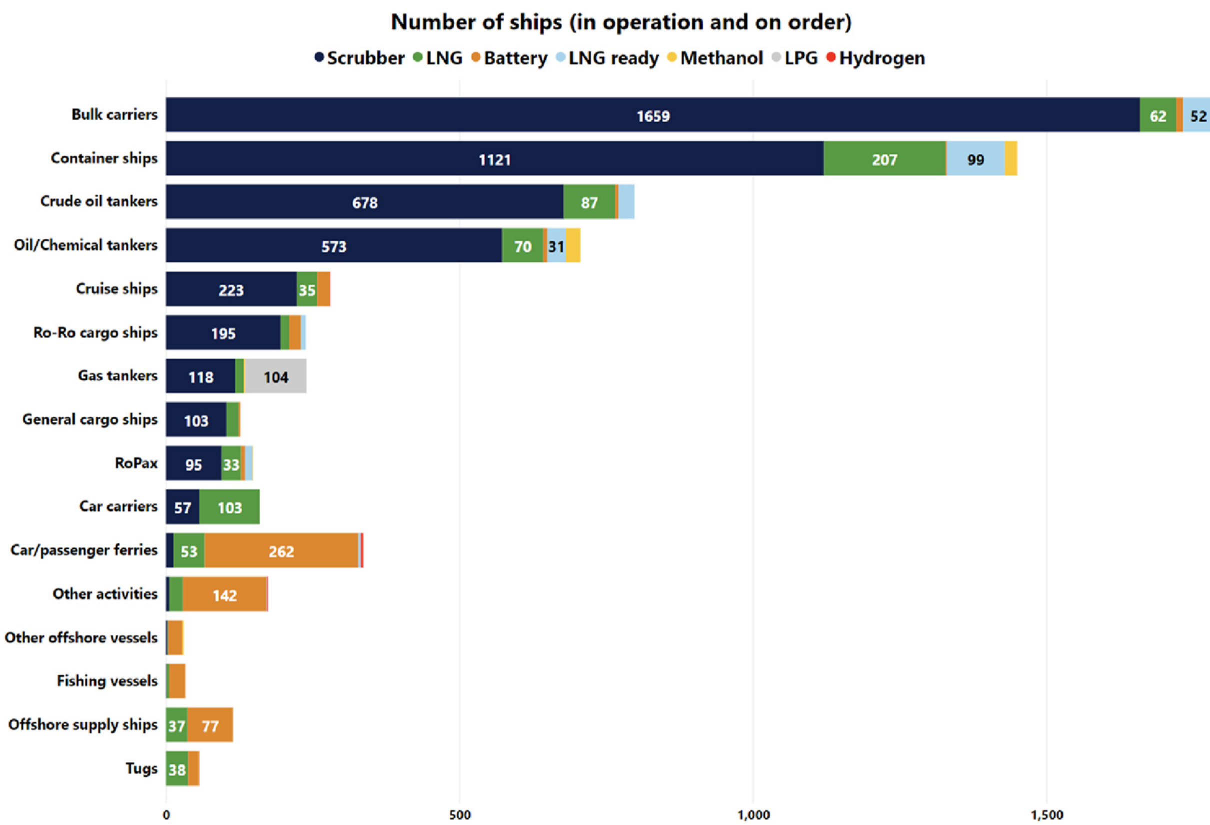

Fig. 5. Current uptake of different fuels in shipping (Alternative Fuels Insight, 2023).

Table 1
Emission factor of traditional fuel (Kim et al., 2020).

	Oil tankers (g/kw)	Gas carriers, chemical carriers, bulk carriers, container ships, Ro-Ros, tugs (g/kw)	Passenger ships (g/kw)
NO_x	29	29	36.40
CO_2	616	605	620
SO_x	9.12	9.47	8.52
PM	1.27	1.25	1.40

and only 5% belong to alternative fuels, including 0.01% methanol ships, 0.19% liquefied natural gas (LNG) ships and 0.3% battery ships. At the same time, there are 11.84% of alternative fuel ships for new ship orders, including 0.02% ammonia, 0.06% hydrogen, 0.3% methanol, and 1.51% liquefied petroleum gas (LPG), 6.10% LNG and 3.85% battery.

Fig. 4 illustrates the change in fuel price used in marine vessels from 2014 to 2022 as the x-axis is the year and the y-axis is the price with USD/tonne as its unit.

Methanol from fossil fuels is the cheapest of the seven categories, with approximately 550 USD/tonne. However, because of the properties of low heating value (19.9 MJ/kg) and no contribution to decreasing emissions, methanol only occupies a very tiny proportion in marine vessels. Fuel oil (3.5% S) is still the most prevalent fuel due to its low price (only about 450 USD/tonne). Ammonia and VLFSO (Very low-sulphur fuel oil) as fuel in marine vessels have slightly higher fuel costs, with roughly 600~700 USD/tonne, and the lower heating values are 18.65 and 40.5 MJ/kg, respectively. Among all existing fuel sources in marine transportation, LPG (liquefied petroleum gas) and LNG (liquefied natural gas) are relatively expensive fuels, with prices reaching about 1100 and 1550 USD/tonne in 2022, accompanied by roughly 46.4 and 50 MJ/kg lower heating values, respectively. The most expensive fuel used in marine vessels in the current stage is biodiesel due

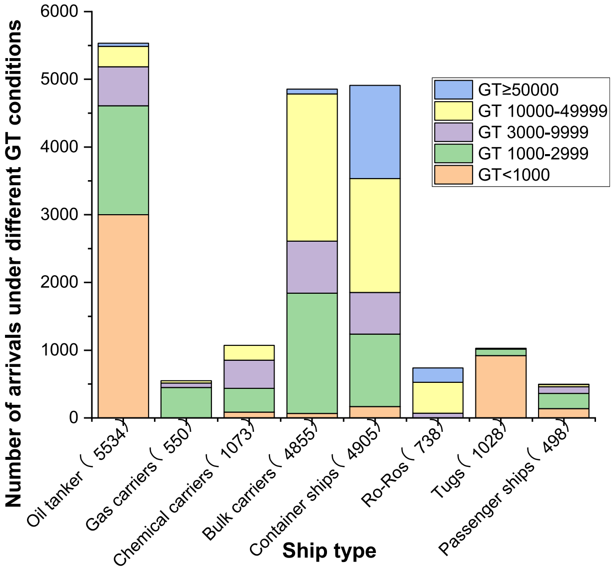

Fig. 6. Vessels arriving in Guangzhou Port in 2016 (Li, 2017).

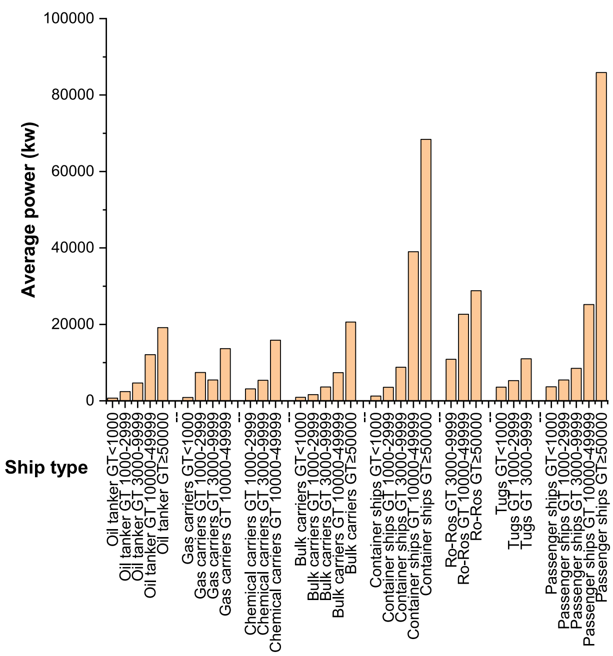

Fig. 7. Engine power of different GT and vessels (Li, 2017).

Table 2
Average duration time when ships released emission in the range of Guangzhou Port in 2016 (Li, 2017).

Ship type	Duration (hours)
Oil tankers	34.37
Gas carriers	35.68
Chemical carriers	29.74
Bulk carriers	29.88
Container ships	28.38
Ro-Ros	23.89
Tugs	12.30
Passenger ships	6.12

to the high collection and torrefaction costs, and the price of biodiesel is approximately 1700 USD/tonne with a 37.2 MJ/kg lower heating value (Alternative Fuels Insight, 2023).

Table 3
Annual pollutant emissions (tonne) in different marine ships (Li, 2017).

Ship type	Annual pollutant emissions (tonne)			
Oil tankers	CO_2	NO_x	SO_x	PM
GT < 1000	15.29	0.40	0.23	0.03
GT 1000~2999	50.52	1.33	0.75	0.10
GT 3000~9999	98.43	2.59	1.46	0.20
GT 10000~49999	255.38	6.72	3.78	0.53
GT ≥ 50000	405.61	10.67	6.01	0.84
Gas carriers				
GT 1000~2999	160.00	3.72	2.50	0.33
GT 3000~9999	117.13	2.72	1.83	0.24
GT 10000~49999	295.39	6.86	4.62	0.61
Chemical carriers				
GT < 1000	16.03	0.37	0.25	0.03
GT 1000~2999	56.08	1.30	0.88	0.12
GT 3000~9999	96.75	2.25	1.51	0.20
GT 10000~49999	285.11	6.62	4.46	0.59
Bulk carriers				
GT < 1000	16.45	0.38	0.26	0.03
GT 1000~2999	29.23	0.68	0.46	0.06
GT 3000~9999	65.60	1.52	1.03	0.14
GT 10000~49999	133.25	3.09	2.09	0.28
GT ≥ 50000	372.39	8.65	5.83	0.77
Container ships				
GT < 1000	21.36	0.50	0.33	0.04
GT 1000~2999	60.75	1.41	0.95	0.13
GT 3000~9999	150.82	3.50	2.36	0.31
GT 10000~49999	669.73	15.55	10.48	1.38
GT ≥ 50000	1174.51	27.28	18.38	2.43
Ro-Ros				
GT 3000~9999	157.22	3.65	2.46	0.32
GT 10000~49999	327.31	7.60	5.12	0.68
GT ≥ 50000	416.53	9.67	6.52	0.86
Tugs				
GT < 1000	27.42	0.46	0.38	0.06
GT 1000~2999	40.29	0.68	0.55	0.09
GT 3000~9999	83.87	1.42	1.15	0.19
Passenger ships				
GT < 1000	13.91	0.24	0.19	0.03
GT 1000~2999	20.62	0.35	0.28	0.05
GT 3000~9999	32.29	0.55	0.44	0.07
GT 10000~49999	95.62	1.62	1.31	0.22
GT ≥ 50000	325.87	5.52	4.48	0.74

Table 4
The average cost of releasing pollutants from ships throughout the year (Yoo et al., 2022; Lu, 2011; Bilgili and Şahin, 2023).

Pollutant cost	Average cost (EUR/ton)
CO_2	56.6
NO_x	16677
SO_x	8030
PM	79500

In Fig. 5, it is evident that traditional fuels still occupy a high proportion of ships, especially in bulk carriers, container ships, crude oil tankers and oil/chemical tankers, with overall 1659, 1121, 678 and 573 vessels, respectively. In addition, 104 gas tanker vessels use LPG, the most extensive application region. The battery is one of the fuel approaches already applied in short-distance ships such as car/passenger ferries and offshore supply ships (Alternative Fuels Insight, 2023).

2.1. Ammonia

Ammonia is one of the most promising alternative fuels for marine vessels in recent times because ammonia is composed of two elements, nitrogen and hydrogen, with no carbon or sulphur. In 2018, MAN B&W, a marine diesel engine manufacturer, announced that its liquefied petroleum gas-fuelled engine will work on injecting ammonia into the ME-LGIP engine within 2~3 years (Zincir, 2020). In addition, ammonia can be produced from fossil fuels and clean energy, such as wind and solar,

Table 5
Total cost of different GT vessel types under different pollutants (traditional fuel) (Li, 2017; Yoo et al., 2022; Lu, 2011).

Ship type	Total cost of different GT vessel types under different pollutants				
Oil tankers	Cost of CO_2 (EUR)	Cost of NO_x (EUR)	Cost of SO_x (EUR)	Cost of PM (EUR)	Total (EUR)
GT < 1000	1.75E+05	9.25E+06	5.46E+06	7.52E+06	2.24E+07
GT 1000~2999	3.09E+05	1.64E+07	9.65E+06	1.33E+07	3.96E+07
GT 3000~9999	2.17E+05	1.15E+07	6.76E+06	9.32E+06	2.78E+07
GT 10000~49999	2.92E+05	1.54E+07	9.11E+06	1.26E+07	3.74E+07
GT ≥ 50000	7.42E+04	3.92E+06	2.31E+06	3.19E+06	9.50E+06
Total	1.07E+06	5.64E+07	3.33E+07	4.59E+07	1.37E+08
Gas carriers					
GT 1000~2999	2.74E+05	1.28E+07	9.03E+06	1.18E+07	3.39E+07
GT 3000~9999	2.99E+04	1.40E+06	9.86E+05	1.29E+06	3.70E+06
GT 10000~49999	3.83E+04	1.79E+06	1.26E+06	1.65E+06	4.74E+06
Total	3.42E+05	1.60E+07	1.13E+07	1.47E+07	4.23E+07
Chemical carriers					
GT < 1000	5.19E+03	2.43E+05	1.71E+05	2.24E+05	6.43E+05
GT 1000~2999	7.54E+04	3.52E+06	2.49E+06	3.25E+06	9.34E+06
GT 3000~9999	1.53E+05	7.13E+06	5.03E+06	6.58E+06	1.89E+07
GT 10000~49999	2.40E+05	1.12E+07	7.92E+06	1.03E+07	2.97E+07
Total	4.73E+05	2.21E+07	1.56E+07	2.04E+07	5.86E+07
Bulk carriers					
GT < 1000	4.20E+03	1.96E+05	1.39E+05	1.81E+05	5.20E+05
GT 1000~2999	1.98E+05	9.24E+06	6.52E+06	8.52E+06	2.45E+07
GT 3000~9999	1.92E+05	8.96E+06	6.32E+06	8.26E+06	2.37E+07
GT 10000~49999	1.10E+06	5.16E+07	3.64E+07	4.76E+07	1.37E+08
GT ≥ 50000	1.02E+05	4.77E+06	3.37E+06	4.40E+06	1.26E+07
Total	1.60E+06	7.47E+07	5.28E+07	6.90E+07	1.98E+08
Container ships					
GT < 1000	1.37E+04	6.39E+05	4.51E+05	5.89E+05	1.69E+06
GT 1000~2999	2.47E+05	1.16E+07	8.16E+06	1.07E+07	3.06E+07
GT 3000~9999	3.54E+05	1.65E+07	1.17E+07	1.53E+07	4.38E+07
GT 10000~49999	4.29E+06	2.01E+08	1.42E+08	1.85E+08	5.31E+08
GT ≥ 50000	6.13E+06	2.86E+08	2.02E+08	2.64E+08	7.59E+08
Total	1.10E+07	5.16E+08	3.64E+08	4.76E+08	1.37E+09
Ro-Ros					
GT 3000~9999	4.19E+04	1.96E+06	1.38E+06	1.81E+06	5.19E+06
GT 10000~49999	5.69E+05	2.66E+07	1.88E+07	2.45E+07	7.04E+07
GT ≥ 50000	3.36E+05	1.57E+07	1.11E+07	1.45E+07	4.17E+07
Total	9.47E+05	4.42E+07	3.12E+07	4.08E+07	1.17E+08
Tugs					
GT < 1000	9.60E+04	3.27E+06	2.78E+06	4.52E+06	1.07E+07
GT 1000~2999	1.49E+04	5.07E+05	4.31E+05	7.02E+05	1.65E+06
GT 3000~9999	3.83E+03	1.31E+05	1.11E+05	1.81E+05	4.26E+05
Total	1.15E+05	3.91E+06	3.32E+06	5.41E+06	1.28E+07
Passenger ships					
GT < 1000	7.31E+03	2.49E+05	2.12E+05	3.45E+05	8.13E+05
GT 1000~2999	1.76E+04	6.00E+05	5.10E+05	8.29E+05	1.96E+06
GT 3000~9999	1.21E+04	4.11E+05	3.49E+05	5.68E+05	1.34E+06
GT 10000~49999	1.24E+04	4.22E+05	3.59E+05	5.84E+05	1.38E+06
GT ≥ 50000	4.96E+03	1.69E+05	1.44E+05	2.34E+05	5.52E+05
Total	5.43E+04	1.85E+06	1.57E+06	2.56E+06	6.04E+06
Overall emission cost of all vessels in Guangzhou port					3.88E+09

to be used as clean energy. The first advantage for future energy sources is that they emit as little as possible of the greenhouse gases that accelerate global warming. Therefore, green ammonia certainly qualifies as a future energy source. In addition, compared to hydrogen, it is easy, cheap and economical to produce, store and transport. Compared with gasoline, the possibility of explosion is lower, so a relatively safe energy source has attracted extensive attention from the international community. Currently, about 80% of ammonia consumption is used in fertilizers such as ammonium nitrate, urea, and ammonium phosphate to improve crop production, and the rest of ammonia is used in health care, explosives, cosmetics, and electronics (Giddey et al., 2017).

The energy density of ammonia is higher than gasoline and methanol: high octane, easy to compress and liquefy, safe and convenient to store and transport. Compared to gasoline, ammonia has a slightly lower heating value but a higher octane rating. By increasing the compression ratio, the thermal efficiency of the engine can be increased to more than 50%, about twice that of a conventional gasoline engine. In addition, because liquid ammonia absorbs heat as it evaporates, ships fuelled by liquid ammonia can be air conditioned almost for free. When it comes to replenishment, the infrastructure of existing gas stations can meet the demand for liquid ammonia replenishment, and synthetic ammonia is one of the most widely produced chemical products in the world. The production, storage, transportation and delivery processes are mature and the existing equipment is suitable.

However, ammonia has yet to be commercialized as a propulsion technology in marine transport. In recent years, many companies have already initiated the use of liquid ammonia in a dual-fuel setup, such as the American Bureau of Shipping and Shanghai Merchant Ship Design & Research Institute had developed ammonia fuelling in the feeder container ship that uses a dual-fuel engine (Hansson et al., 2020). The propulsion system with ammonia fuel is estimated to have between 2% and 60% cost improvement compared to traditional vessels. Meanwhile, the American Bureau of Shipping and Shanghai Merchant Ship Design & Research Institute recognized that replacing offshore ships with ammonia fuel cells is a feasible approach, which has an extra 8%~300% investment because of tremendous uncertainties in cell requirements (Hansson et al., 2020).

Table 6
Total cost of different GT vessel types under different pollutants (Ammonia as fuel) (Li, 2017; Yoo et al., 2022; Lu, 2011; Imhoff et al., 2021).

Ship type	Cost of NO_x (EUR)
Oil tankers	
GT < 1000	1.66E+07
GT 1000~2999	2.93E+07
GT 3000~9999	2.05E+07
GT 10000~49999	2.76E+07
GT ≥ 50000	7.03E+06
Total	1.01E+08
Gas carriers	
GT 1000~2999	2.64E+07
GT 3000~9999	2.88E+06
GT 10000~49999	3.69E+06
Total	3.30E+07
Chemical carriers	
GT < 1000	5.01E+05
GT 1000~2999	7.27E+06
GT 3000~9999	1.47E+07
GT 10000~49999	2.32E+07
Total	4.56E+07
Bulk carriers	
GT < 1000	4.05E+05
GT 1000~2999	1.91E+07
GT 3000~9999	1.85E+07
GT 10000~49999	1.06E+08
GT ≥ 50000	9.85E+06
Total	1.54E+08
Container ships	
GT < 1000	1.32E+06
GT 1000~2999	2.39E+07
GT 3000~9999	3.41E+07
GT 10000~49999	4.14E+08
GT ≥ 50000	5.91E+08
Total	1.06E+09
Ro-Ros	
GT 3000~9999	4.04E+06
GT 10000~49999	5.48E+07
GT ≥ 50000	3.24E+07
Total	9.13E+07
Tugs	
GT < 1000	1.13E+07
GT 1000~2999	1.76E+06
GT 3000~9999	4.53E+05
Total	1.35E+07
Passenger ships	
GT < 1000	8.64E+05
GT 1000~2999	2.08E+06
GT 3000~9999	1.42E+06
GT 10000~49999	1.46E+06
GT ≥ 50000	5.87E+05
Total	6.42E+06
Overall emission cost of all vessels in Guangzhou port	3.02E+09

2.2. Hydrogen

Hydrogen, as the most promising renewable energy source, has numerous areas of research due to its zero pollution during combustion. The United Nations Energy Program has identified hydrogen as the future of the transportation sector. The best approach produces hydrogen, which is called green hydrogen, via electrolysis, converting water into hydrogen and oxygen. Green hydrogen is the only method with no carbon production to form hydrogen. Meanwhile, electricity during the electrolysis process can use renewable energy (wind or solar energy) (Hydrogen, April 13, 2021). The electrolysis technologies have been commercially utilised, but the costs of green hydrogen are considerably higher than the Gray and Blue hydrogen, which is the primary reason for limiting the development. The prevalent solution is to use renewable energy to generate green hydrogen, but it still has a long way to go.

Another essential aspect is hydrogen storage. The most developed and widely used approach is to compress hydrogen. Usually, hydrogen is compressed from 10 to 20~70 MPa to increase hydrogen density and stored by liquefication (Van Hoecke et al., 2021). Apart from this, hydrogenic can be converted to liquid at a low temperature, approximately 21 K, in which the density of hydrogen will enhance to 70.8 kg m^{-3}, about 775 times in comparison with the ambient condition (Van Hoecke et al., 2021). Moreover, hydrogen can be stored using chemical methods, such as metals, alloys, and other chemical substances (Tan et al., 2023). Because the adverse impact is burdensome, the most common approach is to use equation 3 to store hydrogen at 300~500°C and 15~20 MPa (Van Hoecke et al., 2021).

Compared with the energy density of traditional fuels (36.3 MJ L^{-1}), the energy density of liquid hydrogen is relatively low, at only 8.5 MJ L^{-1}. Even without consideration of the thickness of the insulating material, the demand for storage tanks is more than four times that of fossil fuels.

Although hydrogen is regarded as the best option in marine vessels, many vital drawbacks still need to be overcome. Renewable energy is an essential technology to access hydrogen, but hydrogen costs are too high and have not achieved a mature technological level. In addition, the complicated storage system is another bottleneck to gaining highly efficient hydrogen. Further research is concentrating on costs via developing renewable energy production and storage methods and the meaning of green hydrogen.

2.3. Ammonia-hydrogen fuel

Ammonia-hydrogen fuel is another area of research. One of these methods is to add a small amount of hydrogen to the ammonia fuel, which has been found to effectively accelerate combustion, making the engine run more efficiently, especially for SI engines (Comotti and Frigo, 2015). When the hydrogen content of the fuel is 10%, the octane number of the ammonia/hydrogen mixture is higher, and the compression ratio will be further increased to compensate for the intake dilution, increasing the efficiency and adequate pressure (Mørch et al., 2011). Another method, high hydrogen content ammonia, is considered a better solution, and ammonia can be stored as a hydrogen carrier and fuel. The advantage is that ammonia is easily converted to hydrogen. Second, ammonia can be burned or oxidized in an environmentally friendly way. Ammonia can then be synthesized without using fossil fuels as feedstock (Hogerwaard and Dincer, 2016). Mashruk mentioned that an ammonia-hydrogen mixture of 70%~30% volume is much more stable than other conditions. A high hydrogen content (about 30%) causes flashbacks, while a high ammonia mixture (<30%) produces lean blowoff conditions at a low equivalent ratio (Mashruk et al., 2022). NH_3 is characterized by a slow laminar combustion rate, with a significant increase in laminar flame speed with H_2 mixed with NH_3/air mixture. The acceleration of laminar flame velocity increases exponentially with H_2 (Pessina et al., 2022). Under the fuel-rich condition, when the inlet temperature of the mixture is < 1075 K, the NO_x emission of the NH_3–H_2 mixture is slightly higher than the H_2 content, which is proportional to the H_2 content, while the trend is opposite when the inlet temperature of the mixture is higher. At medium and low temperatures, the addition of H_2 hardly improves the reactivity of the system (Manna et al., 2022).

However, compared with other direct hydrogen storage methods, the use of ammonia as a potential hydrogen carrier still receives limited attention. The research mainly focuses on the use of light hydrocarbons and methanol as carriers, but ammonia is undoubtedly more suitable for the emission reduction research on carbon reduction (Klerke et al., 2008).

3. Data resource and method

With the development of technology, some alternative fuels such as ammonia, hydrogen, LNG, e-fuels, biofuels and fuel cells have been used in marine vessels to reduce SO_x, NO_x, CO_2 and other emissions. In the development plan of the coming decades, the proportion of alternative energy will increase, and its role in emission reduction is irreplaceable by traditional energy. In the existing energy potential assessment system, different energy fuels in marine vessels are classified into four levels

Table 7
Total cost of different fuels for ship of different tonnage in Guangzhou Port in 2016 (DNV, 2022; Li, 2017; Yoo et al., 2022; Lu, 2011; Imhoff et al., 2021).

Ship type	Total cost of ammonia fuel for ships of different tonnage (EUR)	Total cost of traditional fuel for ships of different tonnage (EUR)	Total cost of green hydrogen for ships of different tonnage (EUR)
Oil tankers			
GT < 1000	2.92E+07	2.50E+07	6.75E+07
GT 1000~2999	5.17E+07	4.42E+07	1.19E+08
GT 3000~9999	3.62E+07	3.10E+07	8.37E+07
GT 10000~49999	4.88E+07	4.18E+07	1.13E+08
GT ≥ 50000	1.24E+07	1.06E+07	2.86E+07
Gas carriers			
GT 1000~2999	4.66E+07	3.80E+07	1.08E+08
GT 3000~9999	5.09E+06	4.16E+06	1.18E+07
GT 10000~49999	6.51E+06	5.32E+06	1.50E+07
Chemical carriers			
GT < 1000	8.84E+05	7.22E+05	2.04E+06
GT 1000~2999	1.28E+07	1.05E+07	2.96E+07
GT 3000~9999	2.60E+07	2.12E+07	6.00E+07
GT 10000~49999	4.09E+07	3.34E+07	9.44E+07
Bulk carriers			
GT < 1000	7.15E+05	5.84E+05	1.65E+06
GT 1000~2999	3.36E+07	2.75E+07	7.77E+07
GT 3000~9999	3.26E+07	2.66E+07	7.54E+07
GT 10000~49999	1.88E+08	1.53E+08	4.34E+08
GT ≥ 50000	1.74E+07	1.42E+07	4.02E+07
Container ships			
GT < 1000	2.33E+06	1.90E+06	5.37E+06
GT 1000~2999	4.21E+07	3.44E+07	9.72E+07
GT 3000~9999	6.02E+07	4.92E+07	1.39E+08
GT 10000~49999	7.30E+08	5.97E+08	1.69E+09
GT ≥ 50000	1.04E+09	8.52E+08	2.41E+09
Ro-Ros			
GT 3000~9999	7.14E+06	5.83E+06	1.65E+07
GT 10000~49999	9.68E+07	7.90E+07	2.24E+08
GT ≥ 50000	5.73E+07	4.68E+07	1.32E+08
Tugs			
GT < 1000	1.82E+07	1.21E+07	3.68E+07
GT 1000~2999	2.83E+06	1.88E+06	5.71E+06
GT 3000~9999	7.29E+05	4.83E+05	1.47E+06
Passenger ships			
GT < 1000	1.39E+06	9.21E+05	2.80E+06
GT 1000~2999	3.34E+06	2.22E+06	6.75E+06
GT 3000~9999	2.29E+06	1.52E+06	4.62E+06
GT 10000~49999	2.35E+06	1.56E+06	4.75E+06
GT ≥ 50000	9.44E+05	6.26E+05	1.90E+06
Total	4.17E+09	4.11E+09	6.14E+09

according to technical availability, commercial application, safety, flammability, flash point and toxicity, in which the mature technology will give a higher level. In terms of technical availability, safety, available infrastructure, reliable fuel supply, investment cost for infrastructure, investment cost for propulsion and operating cost, ammonia fuel is considered as the most potent fuel in the near future. This paper mainly focuses on evaluating the potential of using ammonia and green hydrogen as fuel for emission reduction and cost benefits for marine applications in a port. Meanwhile, the primary objectives include:

(1) identifying a major port as the case study,
(2) collecting the data on marine vessels, including type, number and fuel consumption,
(3) determining emission factors,
(4) calculating the emissions and overall cost differences between ammonia and conventional fuels,
(5) conducting a cost-benefit analysis between ammonia and green hydrogen.

3.1. The emission factor of traditional fuel in Guangzhou Port

In order to calculate the emission level of different category vessels, the data of average engine power in different Gross Tonnage (GT) ships are listed in Fig. 7.

In order to calculate the amount of emissions in Guangzhou Port, the emission factor of fuel should be collected. In different articles, the values and units are slightly different. Based on different literatures and the specific ship emission situation of Guangzhou Port, the final calculation data adopted in this paper are shown in Table 1, and the unit is g/kw.

3.2. Vessel's size, engine power, fuel type and consumption, mileage information of Guangzhou Port in 2016

In this section, ships arriving at Guangzhou Port in 2016 are regarded as the object of study to research the influence of ammonia or hydrogen as an alternative fuel to displace traditional fuels. First, the number of vessels arriving at Guangzhou Port was collected in Fig. 6, in which vessels are divided into different categories and weights.

Table 2 shows the average duration time when each ship operated nearby the Guangzhou Port in 2016, including cruise, manoeuvring and berthing period.

In the case of ships with different power levels, the power multiplied by the time and the average pollutant emission value gives a picture of the amount of each pollutant emitted by the ship during the year. In this paper, the pollutant emissions are set at the average level when heavy fuel oil is used as fuel, since ships use conventional fuel as their energy source. The emission levels of heavy fuel oil in different categories of ships are given in Table 3. Of course, there are some deviations from the actual situation, mainly due to the lack of statistics on the use of electricity for small tonnage ships and the fact that a small number of ships have used alternative fuels. The results of the annual pollutant emissions are shown in Table 4, and all the emission concentrations are based on the data of Guangzhou Port in 2016, and tons are the unit. To sum up the number of each pollutant in 2016, the figures for CO_2, NO_x, SO_x and PM_{10} emissions using traditional fuel are approximately 4.10E+06, 9.59E+04, 6.39E+04 and 8.49E+03 tons in 2016. Compared to the ammonia fuel shown below, the engines produce only NO_x emissions. If all ships arriving at Guangzhou Port change their fuel to ammonia, the only emission will be 1.97E+05 tons of NO_x per year. Despite a slight increase in NO_x emissions, there is theoretically no other emission., engines only generate NO_x emissions. Despite a slight growth in NO_x emission, there is no other emission theoretically.

3.3. The average environmental cost of different pollutants

Environmental cost is one of the key parameters for evaluating the economics of marine fuels. The costs of dealing with different pollutants are different, and the prices in different regions are slightly different. In this article, the costs are based on the costs of the Atlantic. After integrating the data from several articles, the average costs of dealing with different pollutants are presented in Table 4 (Yoo et al., 2022; Lu, 2011).

4. Results and discussions

4.1. Pollutant cost for different pollutants in Guangzhou Port using traditional fuel

For different categories of ships, the total costs for different pollutants can be calculated and are shown in Table 5. Although the individual emission concentration of smaller tonnage ships is lower than that of large ocean-going ships, the total emission concentration of smaller tonnage ships is higher than that of large ships due to the large number of ships. Meanwhile, because the cost of PM abatement is higher than that of other pollutants, the cost of PM is relatively higher. Among the different types of ships, container ships emit the most, followed by oil tankers.

4.2. Pollutant cost for different pollutants in Guangzhou Port using ammonia

The most proposed alternative fuel in the current stage is ammonia. Imhoff et al. (2021) mentioned the emission level of ammonia. Theoretically, there is no carbon emission and PM generation when using ammonia in marine fuel. However, ammonia will react with intake air, causing a tiny proportion of carbon dioxide and other pollutants. According to the estimation in Imhoff's article, the emission levels of cargo ships and passenger ships are approximately 29 g/kW·h and 36.4 g/kW·h, respectively. However, an SCR (Selective Catalytic Reduction) equation is typically applied in ammonia engines to decrease NO_x generation. In several experiments, SCR has proven that the NO_x concentrations in exhaust gas are roughly 0.029 g/kWh for cargo ships and 0.036 g/kW·h for passenger ships (Imhoff et al., 2021). In terms of the generation of other pollution, the costs are ignored due to the marginal percentage of exhaust gas (Imhoff et al., 2021). The specific costs of different ship types using ammonia as fuel are shown in Table 6.

Compared to emission costs of using traditional fuels and ammonia in marine vessels arriving in Guangzhou port in 2016. the overall emission cost of using ammonia is lower than that of traditional fuels, with 3.02E+09 for ammonia and 3.88E+09 for traditional fuels. Although the emission concentration of NO_x in ammonia is considerably higher than in traditional fuels, ammonia does not generate carbon dioxide and PM, which decreases the emission cost. Theoretically, there is no emission cost when using hydrogen as fuel in marine vessels because only pure water is generated after combustion.

4.3. The cost-benefit analysis and comparison

In the cost-benefit analysis, one of the critical parameters is fuel price. Fuel price includes the price to purchase fuel, storage and delivery. In order to calculate easily, the unit of the fuel price is EUR/MWh. In the alternative fuel price report in 2022 from DNV, the price of ammonia is approximately 0.17 EUR/KW·h, which is considerably higher than fuel oil (0.035 EUR/KW·h) due to the relatively low heating value of ammonia (18.65 MJ/kg) (Alternative Fuels Insight, 2023) and undeveloped production processes. Meanwhile, hydrogen is the most proposed fuel in marine vessels, so the price of green hydrogen should be estimated. According to the survey from the DNV organization, the 2020 price for green hydrogen is approximately 3.1 USD/tonne, and if the price is converted to EUR/KW·h, the price value is about 0.906 EUR/KW·h (DNV, 2022). Meanwhile, the Jiang and Fu (2021) article mentioned that the ammonia price will decrease to 0.13 EUR/KW·h by 2035 and 0.107 EUR/KW·h by 2060, respectively.

Conventional energy is cheaper than alternatives due to years of continuous research and development in extraction, supply and storage. According to the statistical calculation of the cost of traditional energy used by ships in Guangzhou Port in 2016, the cost of traditional fuel purchase is 2.37E+08 EUR. If ammonia is used as fuel instead of traditional energy on the ship, the energy cost is 1.15E+09 EUR. The price of ammonia here is the price of ammonia in the current market, and pollutants are also emitted in the ammonia production process. For a better comparison, Table 7 lists the price of green hydrogen used as an alternative fuel on ships. If all ships arriving at Guangzhou Port in 2016 are replaced with hydrogen as fuel, the energy cost will be about 6.14E+09 EUR. In terms of energy cost, traditional energy occupies the price advantage, but at this stage, the development of alternative energy has just begun, and its various infrastructure could be better. When the environmental costs of emissions and fuel costs are added together, the total cost of different fuels for marine vessels is calculated. For traditional fuel, the total emission cost of all ships in Guangzhou Port is 4.11E+09 EUR, which is lower than the cost of ammonia and green hydrogen, which are 4.17E+09 and 6.14E+09 EUR, respectively.

5. Conclusions

In the present study, Guangzhou Port is used as the target region. A cost-benefit analysis of switching from conventional fuel to ammonia or hydrogen is carried out. The results show that ammonia and hydrogen fuels still do not have a cost advantage in terms of CO_2, SO_x, NO_x and PM_{10} emissions when combined with supply, extraction and storage costs. This is mainly due to the higher expenditure on extraction and storage costs. However, the effect on emission reduction is significant. If ammonia is used to replace conventional fuel in container ships, the original emission levels of 1.02E+07 tonnes of CO_2, 1.59E+05 tonnes of SO_x, 4.88E+05 tonnes of NO_x and 1.01E+03 tonnes of PM_{10} will change to the only emission of 2.37E+05 tonnes of NO_x in 2016. Compared to hydrogen, ammonia has an advantage on the cost-benefit analysis due to the lack of mature commercial methods for storing hydrogen, resulting in extremely high prices for hydrogen storage and transportation. At the present stage, it is indicated that conventional fuel is the most economical fuel compared to ammonia fuel and green hydrogen. Compared to the current price of 0.17 EUR/KW·h, ammonia can decrease to 0.13 EUR/KW·h in 2035, which means that the overall cost of using ammonia as the fuel in Guangzhou Port can decrease to 3.90E+09 EUR. At that time, ammonia as an energy source not only had emission reduction benefits, but also had a lower overall economic cost than conventional fuels. By 2060, the price of ammonia will drop to 0.107 EUR/KW·h, which will give ammonia a greater economic advantage over conventional fuels. In the future, more detailed analysis of different pollutants will be needed, as well as more in-depth research into ammonia storage and transport technology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the 2021 Scientific Research Capacity Improvement Project of Key Construction Discipline of Guangdong Province (No. 2021ZDJS062) and the 2023 Basic and Applied Basic Research Project of Guangzhou Municipal Bureau of Science and Technology (No. SL2022A04J00794). Moreover, Hua Xiao thanks the Department of Education of Guangdong Province for financial support of visit in the UK.

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