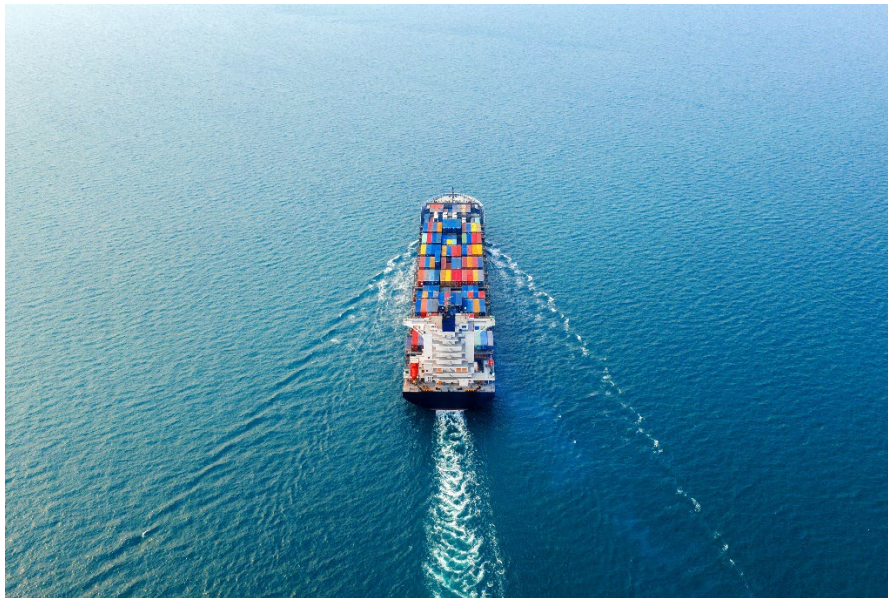


Potential ammonia emissions from ships using ammonia as fuel

Scientific note from DCE – Danish Centre for Environment and Energy

Date: 23 Marts 2026 | 19

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1 Introduction

1.1 Background

Greenhouse gas emissions from global shipping account for around 2-3% of the global greenhouse gas emissions, according to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2022).

The EU's long-term goal for shipping is to be CO₂ neutral by 2050 at the latest, which is in line with the EU's broader climate goals for the union in 2050 and the Paris Agreement.

The International Maritime Organization (IMO), which regulates emissions from ships, has set out in the IMO 2023 strategy a roadmap for reducing greenhouse gas emissions from global shipping, with step-by-step reduction targets in 2030 and 2040 to become CO₂ neutral by 2050 at the latest (IMO, 2023).

Electric propulsion is expected to replace fossil fuels in ferry traffic and shipping only over very short distances, while liquid fuels such as for example e-ammonia produced with Power-to-X are expected to become the dominant fuel type for all other maritime transport. The combustion of sustainable liquid fuels will continue to have environmental impacts on the atmosphere in terms of impacts on air quality. This can have negative impacts in terms of health effects such as premature death and morbidity, as well as on the terrestrial and marine environment in the form of eutrophication from atmospheric nitrogen deposition. In addition, there may be ventilation of tanks as well as spills/accidents that can affect the environment.

When ammonia (NH₃) is burned in a ship engine, several air pollutants are generated: (a) Nitrogen oxides (NO_x), which include nitrogen monoxide (NO) and nitrogen dioxide (NO₂) (b) Unburned ammonia (NH₃) and (c) Nitrous oxide (N₂O).

When pilot fuel such as MDO/MGO (Marine Diesel Oil/Marine Gas Oil) is used to initiate the combustion of ammonia in the engine, this will lead to the emissions of primary particles such as organic matter (OM), elemental carbon (EC) and sulphate (SO₄), as well as sulphur dioxide (SO₂) (from the sulphur content of the diesel fuel). Pilot fuel in ship engines is a small amount of liquid fuel used to initiate combustion in engines that primarily run on a low-ignition fuel such as ammonia.

PM_{2.5} (mass of particulate matter less than 2.5 micrometer) is the largest environmental health hazard. Emissions of NO_x, SO_x and NH_x contribute to formation of PM_{2.5} in the atmosphere and OM, SO₄ and EC are also part of PM_{2.5}. The gases NO₂ and SO₂ are also health hazards by themselves. NO_x also contributes to formation of ozone that is a health hazard.

Deposition of NO_x and ammonia to the marine and terrestrial environment contributes to eutrophication.

N₂O is a very potent greenhouse gas about 265 times as powerful as CO₂.

The negative climate, environmental and health consequences of the combustion of ammonia in ship engines can be limited through regulation and the use of various technological measures.

Presently, there is no specific IMO regulation of ammonia exhaust emissions from maritime engines. For these engines NO_x and SO_x emissions are regulated. For NO_x as limits to the exhaust emissions and for SO_x as limits to the sulphur content in the fuel used (or equivalent emission reduction using an onboard SO_x scrubber). The North Sea and the Baltic Sea are designated as both a Sulphur Emission Control Area (SECA) and a Nitrogen Emission Control Area (NECA). The Baltic Sea includes Kattegat and the Danish sounds according to the definition of HELCOM. The Helsinki Commission (HELCOM) is an intergovernmental organization and a regional sea convention in the Baltic Sea area for protection of the Baltic marine environment.

1.2 Objectives

The Danish Ministry of the Environment and Gender Equality has contacted DCE by email on 13.11.2025 with a small project on potential ammonia emissions from shipping when using ammonia as a fuel. Based on assumptions from the industry about the use of ammonia in international shipping traffic and various assumptions about ammonia emissions, the Ministry wants a rough estimate of the possible extent of the problem by relating the potential ammonia emissions to existing ammonia emissions from shipping in the Baltic Sea as well as from land-based ammonia emissions around the Baltic Sea.

On this basis, a scenario has been developed with the assumption that 30% of the total fuel consumption calculated for ships in the Baltic Sea in 2022 is substituted with ammonia. Furthermore, it is assumed that the ammonia is used in new dual fuel engines that use 95% ammonia and 5% pilot fuel on an energy basis. Various assumptions have been made about ammonia emissions from worst case engine out emissions with no use of aftertreatment to engine out emissions with the use of aftertreatment with catalyst. Assumptions for ammonia slip spans from 10,000 ppm down to 10 ppm.

Chapter 2 describes the detailed assumptions for the scenario, the results for the potential ammonia emissions and relates the results to ammonia emissions from shipping in the Baltic Sea and from land-based emissions around the Baltic Sea.

2 Scenarios for ammonia emissions under different assumptions

2.1 Assumptions

IMO doesn't have any regulation of ammonia exhaust emissions from ship engines and hence there are no limits set for the ammonia emissions for ammonia fueled ships.

Worst case would be no regulation and no aftertreatment of engine out ammonia emissions.

According to papers published by CIMAC (Conseil International des Machines à Combustion), a 2-stroke ammonia dual fuel engine measured by MAN had ammonia emissions of 350 ppm (0.035%) (Hult et al., 2025) and a 4-stroke ammonia dual fuel engine measured by IHI had ammonia emissions of > 10,000 ppm (>1%) as engine out ammonia emissions (Mashima et al., 2025). In the scenario, ammonia emissions of 350 ppm and 10,000 ppm are assumed for engine out emissions as worst case for the two different engine types, respectively.

Ammonia as a fuel for marine traffic is expected to be used in new dual fuel engines that in normal operation use 95% ammonia and 5% diesel pilot fuel on an energy basis and have the same thermal efficiency as conventional diesel engines.

The dual fuel engines are inherently new and new ammonia fueled ships are expected to have to comply with the IMO's Tier 3 requirements for NO_x emissions, which requires the use of a catalyst, which at the same time can reduce the ammonia emissions.

Based on measurement results from the engine manufacturers Japan Engine Corporation, Everllence and WinGD, the ammonia emission for new dual fuel 2-stroke engines, using catalysts, is assumed to be 10 ppm (Ammonia Energy Association, 2025a). Based on measurement results from engine manufacturers IHI and Wärtsilä, the ammonia emissions for new dual fuel 4-stroke engines are assumed to be between 10 ppm and 30 ppm (Ammonia Energy Association, 2025b). In the scenario, ammonia emissions of 10 ppm and 30 ppm are assumed to illustrate technically achievable emissions with aftertreatment. The measured ammonia content in ppm refers to measured ppm in the exhaust gas.

Based on non-stoichiometric combustion fundamentals, the NH₃-emission factors for the best case and worst-case scenarios are calculated in g NH₃/kg NH₃ as described in Annex 1, and the emission factors are shown in Table 2.1.

Table 2.1 NH₃ emission factors calculated for the best case and worst-case scenarios for 2-stroke and 4-stroke dual fuel ammonia engines in this project

| Engine type | NH ₃ emission factors (gNH ₃ /kg NH ₃) | |
|--------------------|--|-------------------------|
| | Best case (with aftertreatment) | Worst case (engine out) |
| 2-stroke dual-fuel | 0.058 | 2.04 |
| 4-stroke dual-fuel | 0.058/0.18 | 58.36 |

2.2 Method for calculations

For the Baltic Sea, Jalkanen et al. (2023) have calculated the total fuel consumption in ktonnes and NH₃ emissions for shipping traffic in the Baltic Sea as a baseline for the year 2022. The fuel consumption is subsequently converted to TJ based on a weighted calorific value of 42.29 GJ/tonne, corresponding to a consumption distribution of 80% MDO/MGO and 20% HFO in the Baltic Sea found by Jalkanen et al. (2023). MDO, MGO and HFO are Marine Diesel Oil, Marine Gas Oil and Heavy Fuel Oil, respectively.

The calculations are carried out assuming that 30% of the total fuel consumption of HFO/MDO/MGO calculated for ships in the Baltic Sea in 2022 is substituted with ammonia. It is assumed that the ammonia is used in new dual fuel engines that use 95% NH₃ and 5% pilot fuel on an energy basis and have the same thermal efficiency as conventional diesel engines.

There is no information about the breakdown of fuel consumption on 2- and 4 stroke engines in Jalkanen et al. (2023). Therefore, the calculations do not distinguish between 2-stroke and 4-stroke engines, instead the NH₃ emission consequences are calculated for different assumption of ammonia emissions.

2.3 Results

2.3.1 Engine out with no after treatment

Table 2.2 shows the results for the worst-case scenario with engine out ammonia emissions of 350 ppm and 10,000 ppm and no aftertreatment. The table shows the consumption (ktonnes and TJ) and NH₃ emissions (ktonnes) for the baseline in the Baltic Sea. It also shows the NH₃ fuel consumption (ktonnes and TJ) and NH₃ emissions (ktonnes) in the calculation where 30% of conventional fuel is replaced with ammonia in the Baltic Sea. The total calculated NH₃ emissions when 70% conventional fuel and 30% ammonia are used are also shown for the two NH₃ slip calculations.

Table 2.2. Fuel consumption and NH₃ emissions in Baseline, NH₃ use and NH₃ emissions for the part of fuel substituted with ammonia, and total ammonia emissions from fossil fuel + ammonia fuel.

| Baseline | | | Fuel substituted with ammonia | | | | Total NH ₃ emissions from fossil fuel + ammonia fuel | |
|------------------|---------------------------|--------|-------------------------------|---------------------|--------------------------|--------------------------|---|------------|
| Fuel consumption | NH ₃ emissions | | NH ₃ use | NH ₃ use | NH ₃ emission | NH ₃ emission | 350 ppm | 10,000 ppm |
| ktonne | TJ | ktonne | TJ | ktonne | ktonne | ktonne | ktonne | ktonne |
| 4,301 | 181,889 | 0.07 | 54,567 | 2,934 | 5.99 | 171.22 | 6.04 | 171.27 |

2.3.2 With after treatment

The new dual fuel engines fueled with ammonia are expected to have to comply with the IMO's Tier 3 requirements for NO_x emissions, which requires the use of a catalytic converter that also can reduce ammonia emissions.

Table 2.3 shows the results for fuel consumption and NH₃ emissions for the baseline in the Baltic Sea, as well as NH₃ fuel consumption and NH₃ emissions at 10 ppm and 30 ppm ammonia emissions, respectively, assuming aftertreatment. In the calculation, 30% of conventional fuel is replaced with ammonia

in the Baltic Sea. The total calculated NH₃ emissions when 70% conventional fuel and 30% ammonia are used are also shown for the two NH₃ slip calculations.

Table 2.3. Fuel consumption and NH₃ emissions in Baseline, NH₃ use and NH₃ emissions for the part of fuel substituted with ammonia and total ammonia emissions from fossil fuel + ammonia fuel.

| Baseline | | | Fuel substituted with ammonia | | | | Total NH ₃ emissions from fossil fuel + ammonia fuel | |
|------------------|---------------------------|--------|-------------------------------|---------------------|--------------------------|--------------------------|---|--------|
| Fuel consumption | NH ₃ emissions | | NH ₃ use | NH ₃ use | NH ₃ emission | NH ₃ emission | 10 ppm | 30 ppm |
| ktonne | TJ | ktonne | TJ | ktonne | ktonne | ktonne | ktonne | ktonne |
| 4,301 | 181,889 | 0.07 | 54,567 | 2,934 | 0.17 | 0.51 | 0.22 | 0.56 |

2.3.3 Comparison with land-based ammonia emissions

Table 2.4 shows the land-based NH₃ emissions for the HELCOM countries for 2022, received from Svendsen (2025).

Table 2.4. National NH₃ emissions for land-based emission sources in the HELCOM countries in 2022

| HELCOM country | NH ₃ emission (ktonne) |
|---------------------|-----------------------------------|
| Denmark | 73 |
| Estonia | 10 |
| Finland | 30 |
| Germany | 577 |
| Latvia | 13 |
| Lithuania | 35 |
| Poland | 293 |
| Russian Federation | 1,162 |
| Sweden | 54 |
| Total HELCOM | 2,248 |

In the baseline where conventional marine fuel is used, the NH₃ emissions of 0.07 ktonnes from shipping in the Baltic Sea correspond to approx. 0.003% of total ammonia emissions for land-based sources of the countries bordering the Baltic Sea and participating in the HELCOM Convention (the HELCOM countries).

Derived from Table 2.1, NH₃ emissions from ship traffic will increase from 0.07 ktonnes to 6.04 ktonnes and to 171.27 ktonnes by an ammonia release from the ship engines of 350 ppm and 10,000 ppm, respectively, in the engine out worst-case scenario. In this engine out scenario, the ammonia ship emissions are approx. 0.3% and 7.6% of the total land-based ammonia emissions from all the HELCOM countries, respectively, for ammonia slip of 350 ppm and 10,000 ppm.

Derived from the figures in Table 2.2, NH₃ emissions from ship traffic will increase from 0.07 ktonnes to 0.22 and 0.56 ktonnes, respectively, by an ammonia release from the ship engines of 10 ppm and 30 ppm in the scenario

with aftertreatment. Compared to the land-based NH_3 emissions of the HELCOM countries, NH_3 emissions from shipping in the Baltic Sea are marginal in this scenario. In the scenario where 30% of the conventional fuel is replaced with ammonia and the NH_3 emission is 30 ppm, the NH_3 emissions from shipping in the Baltic Sea correspond to approx. 0.02% of ammonia emissions from all the HELCOM countries.

The results are thus very sensitive to assumptions about ammonia exhaust emissions from ships. A worst-case scenario, assuming engine out ammonia emissions and no aftertreatment, will result in increase of ammonia emissions up to 8 % of total HELCOM land-based emissions whereas a scenario with aftertreatment will have small ammonia emissions of up to 0.02% of total HELCOM land-based emissions illustrating the potential for regulation of ammonia exhaust emissions from ammonia fueled ships.

The scenario assumed that 30% of the conventional fuel is replaced with ammonia, and ammonia emissions would be proportionally different if a different percentage is substituted.

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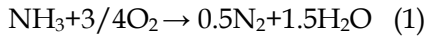
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Annex 1 Calculation of NH₃ emission factors

1. Description of the engine combustion of NH₃

1.1 Stoichiometric combustion

The combustion equation for stoichiometric combustion of NH₃ is as follows:



In the following we regard the combustion of 1 kg NH₃. Atom weights are known for H = 1, N = 14 and O = 16. This enables the calculation of the molar mass, M (g/mole) and the reciprocal molar mass (mole/kg) for NH₃, shown in Table 1:

Table 1 Molar mass, M (g/mole) and reciprocal molar mass 1/M (mole/kg) for NH₃.

| Molar mass (M) for NH ₃ , g/mole | Reciprocal molar mass (1/M) for NH ₃ Mole/kg |
|--|--|
| 14 + 3*1 = 17 | 58.8 |

Hence, 58.8 mole NH₃ is used as input for the combustion (left side of combustion equation (1)), and mole O₂ per kg NH₃ input fuel in the engine is calculated as:

$$3/4 * 58.8 \text{ mole O}_2 = 44.1 \text{ mole O}_2 \quad (2)$$

As output from the combustion (right side of combustion equation (1)) 0.5 mole dry exhaust gas (N₂) is generated per mole NH₃. Mole dry exhaust gas (N₂) per kg NH₃ consumed is hence calculated as:

$$(0.5 \text{ mole/mole NH}_3) * (58.8 \text{ mole NH}_3) = 29.4 \text{ mole dry exhaust gas} \quad (3)$$

Knowing that the atmospheric content of O₂ = 20.95% (O₂ molecules per volume of atmospheric air), the number of moles that are not O₂ ("non-O₂") in the input air per kg of NH₃ consumed can be determined as:

$$\text{Mole "non-O}_2\text{" in the input air} = (44.1 \text{ mole O}_2 / 0.2095) * (1 - 0.2095) = 166.5 \text{ mole} \quad (4)$$

Assuming stoichiometric combustion, the total number of moles of dry exhaust gas, (including "non-O₂") per kg of NH₃ consumed can then be determined as the sum of the number of moles in dry exhaust gas (N₂) per kg of NH₃ consumed found in (3) and the number of moles of "non-O₂" in exhaust flue gas per kg of NH₃ consumed found in (4):

$$\text{total moles dry exhaust gas (including "non-O}_2\text{") per kg NH}_3 \text{ consumed} = (29.4 \text{ mole} + 166.5 \text{ mole}) = 195.9 \text{ mole} \quad (5)$$

1.2 Non-stoichiometric combustion

During combustion in the engine, there is typically an excess of air. This excess air consists of O₂ and the part of the air that is not O₂ ("non-O₂"). The excess air passes through the engine without being part of the combustion. The excess air must be considered when determining the final number of moles of dry exhaust gas that the exhaust gas contains. The excess air for the combustion in the engine is described by the air-fuel ratio Lambda (λ).

The total number of moles of dry exhaust gas per kg NH₃, including excess moles of O₂ and “non-O₂” at a given air-fuel ratio (λ), is thus calculated by inserting the values calculated in (5), (2) and (4) into the following expression:

$$\begin{aligned} &= \text{total stoichiometric moles dry exhaust gas} + (\text{mole O}_2 + \text{mole "non-O}_2\text{" in the input air}) * (\lambda - 1) \\ &= 195.9 \text{ mole} + (44.1 \text{ mole} + 166.5 \text{ mole}) * (\lambda - 1) \quad (6) \end{aligned}$$

2. NH₃ emission factors for 2-stroke and 4-stroke engines calculated from exhaust gas measurements of NH₃

During normal engine running, the air-fuel ratio λ is 1.7 in both cases for ammonia dual-fuel 2-stroke engines and for ammonia dual-fuel 4-stroke engines (Everllence, 2026).

By insertion of $\lambda = 1.7$ in (6), the total moles of dry exhaust gas per kg NH₃, including excess moles of O₂ and “non-O₂”, is calculated for 2-stroke and 4-stroke ammonia dual-fuel engines as:

$$\begin{aligned} \text{2-stroke engines: } &195.9 \text{ mole} + (44.1 \text{ mole} + 166.5 \text{ mole}) * (1.7 - 1) = 343.3 \text{ mole} \quad (7a) \\ \text{4-stroke engines: } &195.9 \text{ mole} + (44.1 \text{ mole} + 166.5 \text{ mole}) * (1.7 - 1) = 343.3 \text{ mole} \quad (7b) \end{aligned}$$

The ratio between the total number of moles of dry exhaust gas per kg NH₃ calculated in (7) and the total number of moles of NH₃ per kg NH₃ expresses the “molar expansion” from 1 kg of NH₃ input fuel to the number of moles in the total volume of the exhaust gas. It is this total exhaust gas volume that emission measurements in the exhaust gas are related to, measured as ppm (ppm vol.).

According to papers published by CIMAC (Conseil International des Machines à Combustion), a 2-stroke ammonia dual fuel engine measured by MAN had ammonia emissions of 350 ppm (0.035%) (Hult et al., 2025) and a 4-stroke ammonia dual fuel engine measured by IHI had ammonia emissions of > 10,000 ppm (>1%) as engine out ammonia emissions (Mashima et al., 2025). Ammonia emissions of 350 ppm and 10,000 ppm are assumed for engine out emissions as worst case for the two different engine types, respectively.

Based on measurement results from the engine manufacturers Japan Engine Corporation, Everllence and WinGD, the ammonia emission for new dual fuel 2-stroke engines, using catalysts, is assumed to be 10 ppm (Ammonia Energy Association, 2025a). Based on measurement results from engine manufacturers IHI and Wärtsilä, the ammonia emissions for new dual fuel 4-stroke engines are assumed to be between 10 ppm and 30 ppm (Ammonia Energy Association, 2025b). Ammonia emissions of 10 ppm and 30 ppm are assumed as best case to illustrate technically achievable emissions with aftertreatment.

For a given measured amount of NH₃ in the exhaust gas (ppm volume), the final emission is obtained in gNH₃ per kg NH₃, using as input the amount of mole of dry exhaust gas and the mole weight of ammonia:

$$E_{\text{NH}_3} = \text{ppm NH}_{3\text{measured}} * 10^{-6} * (343.3 \text{ mole} * 17\text{g}/\text{mole}) \quad (8)$$

Where:

E_{NH_3} = Emissions of NH₃ per kg NH₃ consumed

ppm = measurement value of NH₃ in the exhaust gas (ppm vol.)

Table 2 contains an overview of the measured ppm values for NH₃ in the exhaust gas used in the best case and worst-case scenarios for 2-stroke and 4-stroke dual fuel ammonia engines in this project.

Table 2 measured ppm values for NH₃ in the exhaust gas used in the best case and worst-case scenarios for 2-stroke and 4-stroke dual fuel ammonia engines in this project

| Engine type | NH ₃ (ppm vol.) measured in the exhaust gas | |
|--------------------|--|------------|
| | Best case | Worst case |
| 2-stroke dual-fuel | 10 ppm | 350 ppm |
| 4-stroke dual-fuel | 10 ppm/30 ppm | 10,000 ppm |

By insertion in (8) the best case and worst case NH₃ emission factors for the 2-stroke and 4-stroke ammonia dual-fuel engines are calculated as:

2-stroke engines

$$\text{Best case: } E_{\text{NH}_3} = 10 \text{ ppm} * 10^{-6} * (343.3 \text{ mole} * 17 \text{ g/mole}) = 0.058 \text{ g NH}_3/\text{kg NH}_3$$

$$\text{Worst case: } E_{\text{NH}_3} = 350 \text{ ppm} * 10^{-6} * (343.3 \text{ mole} * 17 \text{ g/mole}) = 2.04 \text{ g NH}_3/\text{kg NH}_3$$

4-stroke engines

$$\text{Best case: } E_{\text{NH}_3} = 10 \text{ ppm} * 10^{-6} * (343.3 \text{ mole} * 17 \text{ g/mole}) = 0.058 \text{ g NH}_3/\text{kg NH}_3$$

$$\text{Best case: } E_{\text{NH}_3} = 30 \text{ ppm} * 10^{-6} * (343.3 \text{ mole} * 17 \text{ g/mole}) = 0.18 \text{ g NH}_3/\text{kg NH}_3$$

$$\text{Worst case: } E_{\text{NH}_3} = 10,000 \text{ ppm} * 10^{-6} * (343.3 \text{ mole} * 17 \text{ g/mole}) = 58.36 \text{ g NH}_3/\text{kg NH}_3$$

Table 3 contains an overview of the NH₃ emission factors calculated for the best case and worst-case scenarios for 2-stroke and 4-stroke dual fuel ammonia engines in this project.

Table 3 NH₃ emission factors (EF) calculated for the best case and worst-case scenarios for 2-stroke and 4-stroke dual fuel ammonia engines in this project

| Engine type | EF NH ₃ (gNH ₃ /kg NH ₃) | |
|--------------------|--|------------|
| | Best case | Worst case |
| 2-stroke dual-fuel | 0.058 | 2.043 |
| 4-stroke dual-fuel | 0.058/0.18 | 58.36 |

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