# ADVANCES IN SUSTAINABLE AND TECHNOLOGICAL MARITIME SOLUTIONS

EDITORS :
PROF. HAKKI DERELİ
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# PREFACE

The Faculty of Naval Architecture and Maritime at Izmir Kâtip Celebi University aims to train qualified engineers for the maritime sector through undergraduate education. In addition to this aim, the scientific studies and knowledge produced by the faculty members will be shared with the academic community and the maritime sector through books to be published each year.

This first book, consisting of 9 chapters, covers environmental sustainability and technological innovations in the maritime sector. Developments in these areas aim to reduce the environmental impacts of maritime transport and the shipbuilding industry, which is an important part of global trade, while at the same time increasing operational efficiency.

We would like to express our sincere gratitude to our faculty members who wrote the chapters and Uğur Ekenoğlu who designed the cover, and we hope to contribute many of our books to the literature in the future.

December 20, 2024

Editors Prof. Hakkı DERELİ, Assoc. Prof. Mehmet ÖNAL

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# CHAPTER I

# AN ANALYSIS ON THE CONSTRUCTION OF THE TURKISH MARINE FISHING FLEET

Hakkı DERELİ[1], Hüseyin AKBAŞ[2]

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## ABSTRACT

Collecting and analyzing information on fishing fleets is necessary and important in order to assess the size of the fleets and determine future strategies in fisheries management. The aim of this chapter was to analyse the construction of the Turkish marine fishing fleet. The database of the commercial fishing fleet of the General Directorate of Fisheries and Aquaculture of the Ministry of Agriculture and Forestry constituted the material of the study. Data on the age, length, engine power and construction material of the vessels were used. Descriptive statistics were given for the whole fleet and according to fishing gear. Differences between the fishing gear groups were tested. The whole fleet consists of 51.8% gillnet, 18.1% longline, 16% other, 5.8% beam trawl, 3.8% single boat bottom otter trawl, 3.2% purse seine, 1.2% mid-water pelagic trawl and 0.1% pot vessels. 86.6% of the all fleet consists of wood, 9.7% sheet metal and 3.7% fiberglass/plastic vessels. Purse seine, mid-water pelagic trawl and single boat bottom otter trawl vessels, defined as industrial fisheries or large-scale fisheries, had higher length and engine power values with a statistically significant difference ($p = 0.001$) than the other five fishing gear groups using vessels with lengths less than 12 m, defined as small-scale fisheries. It is thought that the analysis in this chapter will assist fisheries decision-makers in their arrangements for the fleet and provide a basis for further analysis.

**Keywords**: Fishing fleet, fishing gear, length, engine power, construction material, Türkiye

## 1. INTRODUCTION

Capture fisheries, which are important in terms of supplying animal protein, contribute to nutrition, food security, sustainable livelihoods, poverty reduction and employment (Berkes et al., 2001; Sağlam and Düzgüneş, 2010; Boyd et al., 2022; FAO, 2024).

This important sector can be divided into two groups: large-scale fisheries (LSF) and small-scale fisheries (SSF), which differ in terms of the fishing gear used and technology, capital, and labor requirements. Large-scale fisheries generally consist the purse seine and trawls, which require larger vessel and engine power and the number of workers required. Small-scale fisheries in the Mediterranean Sea and Black Sea where Türkiye is located, are characterised by the use of small vessels and a highly heterogeneous mix of landing locations, gear types (e.g., gillnets, trammel nets, combined nets, longlines), fishing strategies and target species (FAO, 2022).

Turkish marine fisheries use a variety of fishing gears in the Black Sea (GSA 29), Marmara Sea (GSA 28), North Levant (GSA 24), and Aegean Sea (GSA 22). Along with the development in the Turkish economy, fishing industry has also developed in the vessel construction and fishing gear manufacturing. Being supported by subsidizes from the government, Turkish fishing fleet became an important power in the surrounding seas (Sağlam and Düzgüneş, 2010). LSF vessels are usually comprised of sheet metal, using otter bottom trawlers (OTB), and purse seiners with encircling nets (PS), with SSF vessels, most of which are wooden, including trammel and gill netters, long-liners, traps, beam trawls, etc., operate along all the coasts (Dereli et al., 2024).

When scientific studies on the Turkish fishing fleet are examined, it is seen that the focus is generally on the fleet in a certain region or on some fishing gear groups, and that there are very few studies that address the whole fleet. Sağlam and Düzgüneş (2010) reviewed to Turkish fishing fleet using such profitability indicators such as catch per unit effort (tonnage, engine power), age of the vessels etc, employed. Dereli and Belli (2014), determined changes in the 29 years period (1985-2013) of the fishing fleet of Muğla Province located South Aegean coast of Türkiye and the existing vessel features. Düzgüneş et al. (2014), examined the structure of the Turkish fishing fleet in the Black Sea. The current status, importance and challenges of SSF in Türkiye have been presented in a number of studies (Ünal and Ulman, 2020; Dereli and Akbaş, 2023). Dereli et al. (2024) presented the age, length, tonnage and HP changes of the Turkish purse seine and trawl fleets in the Aegean Sea between 2011 and 2021.

Collecting and analyzing information on fishing fleets is necessary and important in order to assess the size of the fleets and determine future strategies in fisheries management (Dereli and Belli, 2014; FAO, 2024). Therefore, this chapter aimed to analyze the construction of the Turkish marine fishing fleet.

The material of this study consisted the commercial fishing fleet database (as of November 1, 2024) of the General Directorate of Fisheries and Aquaculture of the Ministry of Agriculture and Forestry. Data on the age, construction material, length and engine power of the vessels were used. Fishing gears were classified according to the International Standard Statistical Classification of Fishing Gear (ISSCFG) (Revision 1) of The Food and Agriculture Organization (FAO) (FAO, 2016). ISSCFG codes and standard abbreviations of fishing gears are shown in parentheses. Fishing gears were grouped as purse seine (PS) (01.1), single boat bottom otter trawls (OTB) (03.12) (in the remainder of the text as bottom trawl), mid-water pelagic trawls (PTM) (03.22) (in the remainder of the text as mwp trawl), set gillnets (anchored) (GNS) (07.1) and trammel nets (GTR) (07.5) (in the remainder of the text as gillnet), beam trawl (TBB) (03.11) (called Algarna), set longlines (LLS) (09.31) (in the remainder of the text as longline), pots (FPO) (08.2) and fyke nets (FYK) (08.3) (in the remainder of the text as pot), handlines and hand-operated pole-and- lines (LHP) (09.1) and mechanized lines and pole-and-lines (LHM) (09.2) and other gears/methods (in the remainder of the text as other).

The data were evaluated in the IBM SPSS Statistics 22.0 (IBM Corp., Armonk, New York, USA) statistical package program. Descriptive statistics were given for the whole fleet and according to fishing gear as number of units (n), percentage (%), mean±standard deviation ($\bar{x}\pm sd$) values. The normal distribution of the data of numerical variables was evaluated with the Shapiro Wilk normality test and Q-Q graphs. Comparisons between fishing gear groups were made with with Kruskal-Wallis analysis for non-normally distributed variables. For multiple comparisons, the Bonferroni test was used for non-normally distributed variables. A value of $p<0.05$ was considered statistically significant.

## 2. TURKISH MARINE FISHING FLEET

The Turkish marine fishing fleet consists of vessels using purse seine, mwp trawl, trawl, beam trawl, other, longline, pot and gillnet. The number of vessels in each fishing gear group is presented in Table 1 according to the sea in where they are registered. Of the total of 15,111 vessels in the Turkish marine fishing fleet, 35% are registered in the Sea of Marmara and Straits, 34% in the Black Sea, 20% in the Aegean Sea and 11% in the Mesiterranean Sea. The whole fleet consists of 51.8% gillnet, 18.1% longline, 16% other, 5.8% beam trawl, 3.8% trawl, 3.2% purse seine, 1.2% mwp trawl and 0.1% pot vessels (Table 1).

It was found that 19.4% (2,937 vessels) out of 15,111 vessels in the fishing fleet database had missing of construction year information, and therefore descriptive statistics and comparisons between groups for vessel age were not made.

**Table 1.** The vessels number in each fishing gear group according to the sea

| Fishing gear | Black Sea | Sea of Marmara and Straits | Aegean Sea | Mediterranean Sea | Total |
|---|---|---|---|---|---|
| **Purse seine** | 128 | 239 | 69 | 51 | **487** |
| **Trawl** | 107 | 244 | 51 | 166 | **568** |
| **Mwp trawl** | 112 | 63 | 0 | 1 | **176** |
| **Gillnet** | 2,992 | 2,695 | 1,420 | 723 | **7,830** |
| **Beam trawl** | 606 | 266 | 6 | 3 | **881** |
| **Longline** | 410 | 520 | 1256 | 554 | **2,740** |
| **Pot** | 1 | 3 | 12 | 2 | **18** |
| **Other** | 742 | 1,297 | 273 | 117 | **2,411** |
| **Total** | **5,098** | **5,327** | **3,087** | **1,617** | **15,111** |

### 2.1. Construction Material

The number of vessels in each fishing gear group by construction material is shown in Table 2. 86.6% of the all fleet consists of wood, 9.7% sheet metal and 3.7% fiberglass/plastic vessels. When evaluated according to the fishing gear, wood material has the highest percentage values in gillnet (94.1%), beam trawl (88.8%), longline (96.5%), pot (100%) and other (87.3%). (Table 2).

Sheet metal has the highest percentage values in purse seine (87.1%), trawl (79.8%), mwp trawl (100%). The percentage of fiberglass/plastic varied between 0 and 5.2 per cent in the fishing gear groups (Table 2).

**Table 2.** The vessels number in each fishing gear group by construction material

| Fishing gear | Material | N | % |
|---|---|---|---|
| **Purse seine** | **Wood** | 63 | 12.9 |
| | **Fiberglass/Plastic** | 0 | 0.0 |
| | **Sheet metal** | 424 | 87.1 |
| **Trawl** | **Wood** | 114 | 20.1 |
| | **Fiberglass/Plastic** | 1 | 0.2 |
| | **Sheet metal** | 453 | 79.8 |
| **Mwp trawl** | **Wood** | 0 | 0.0 |
| | **Fiberglass/Plastic** | 0 | 0.0 |
| | **Sheet metal** | 176 | 100.0 |
| **Gillnet** | **Wood** | 7,368 | 94.1 |
| | **Fiberglass/Plastic** | 319 | 4.1 |
| | **Sheet metal** | 143 | 1.8 |
| **Beam trawl** | **Wood** | 782 | 88.8 |
| | **Fiberglass/Plastic** | 19 | 2.2 |
| | **Sheet metal** | 80 | 9.1 |
| **Longline** | **Wood** | 2,643 | 96.5 |
| | **Fiberglass/Plastic** | 88 | 3.2 |
| | **Sheet metal** | 9 | 0.3 |
| **Pot** | **Wood** | 18 | 100.0 |
| | **Fiberglass/Plastic** | 0 | 0.0 |
| | **Sheet metal** | 0 | 0.0 |
| **Other** | **Wood** | 2,104 | 87.3 |
| | **Fiberglass/Plastic** | 126 | 5.2 |
| | **Sheet metal** | 181 | 7.5 |
| **Total** | **Wood** | **13,092** | **86.6** |
| | **Fiberglass/Plastic** | **553** | **3.7** |
| | **Sheet metal** | **1,466** | **9.7** |

### 2.2. Length and Engine Power

Descriptive statistics of fishing gear groups on length (m) and engine power (kW) are presented in Table 3. The highest mean length value was in vessels using purse seine, followed by vessels using mwp trawl, trawl, beam trawl, other, longline, pot and gillnet, respectively. The ranking in terms of engine power was purse seine, mwp trawl, trawl, beam trawl, other, gillnet, longline and pot (Table 3).

**Table 3.** Descriptive statistics of fishing gear groups on length (m) and engine power (*n*: number; $\bar{x}\pm sd$: mean±standard deviation; *CI*: 95% confidence interval; L: lower bound; U: upper bound)

| **Fishing gear** | | **Length (m)** | **Engine power (kW)** |
|---|---|---|---|
| **Purse seine** (*n*=487) | $\bar{x}\pm sd$ | 29.04±11.25 | 1,267.24±1,072.32 |
| | *CI* (L-U) | 28.04-30.04 | 1,171.77-1,362.72 |
| **Trawl** (*n*=568) | $\bar{x}\pm sd$ | 18.25±5.32 | 449.15±303.83 |
| | *CI* (L-U) | 17.81-18.69 | 424.11-474.19 |
| **Mwp trawl** (*n*=176) | $\bar{x}\pm sd$ | 22.75±5.15 | 831.10±375.34 |
| | *CI* (L-U) | 21.99-23.52 | 775.27-886.94 |
| **Gillnet** (*n*=7,828) | $\bar{x}\pm sd$ | 7.44±1.86 | 55.99±67.11 |
| | *CI* (L-U) | 7.40-7.48 | 54.50-57.47 |
| **Beam trawl** (*n*=881) | $\bar{x}\pm sd$ | 8.36±2.75 | 93.23±93.94 |
| | *CI* (L-U) | 8.18-8.54 | 87.01-99.44 |
| **Longline** (*n*=2,739) | $\bar{x}\pm sd$ | 7.46±1.55 | 44.88±53.20 |
| | *CI* (L-U) | 7.40-7.51 | 42.89-46.87 |
| **Pot** (*n*=18) | $\bar{x}\pm sd$ | 7.45±1.25 | 40.92±43.80 |
| | *CI* (L-U) | 6.83-8.07 | 19.14-62.70 |
| **Other** (*n*=2,411) | $\bar{x}\pm sd$ | 8.31±4.70 | 92.15±203.20 |
| | *CI* (L-U) | 8.13-8.50 | 85.13-99.17 |

When the length values of the fishing gear groups were compared statistically, it was found that purse seines, mwp trawlers and trawlers had higher length values and there was a statistically significant difference between them and the other five fishing gear groups (beam trawl, other, gillnet, longline and pot) (*p*= 0.001). Among the five gear groups with median values between 7.2 and 8 m, a statistically significant difference was found between beam trawl and the other three gear groups (other, gillnet, longline) (*p*= 0.001) (Table 3 and Figure 1).

**Table 4.** Comparison of length and engine power values of fishing gear groups (*IQR*: Interquartile range)

| **Fishing gear** | | **Length (m)** | **Engine power (kW)** |
|---|---|---|---|
| **Purse seine** | *Median*<br>*(IQR)* | 30.12 $^{a}$<br>(18.87) | 903.76 $^{a}$<br>(1,432.19) |
| **Trawl** | *Median*<br>*(IQR)* | 17.62 $^{a}$<br>(8.26) | 358.21 $^{b, a}$<br>(233.70) |
| **Mwp trawl** | *Median*<br>*(IQR)* | 23.00 $^{a}$<br>(6.39) | 807.48 $^{c, a}$<br>(311.17) |
| **Gillnet** | *Median*<br>*(IQR)* | 7.25 $^{b}$<br>(2.14) | 26.12 $^{d, \imath}$<br>(65.68) |
| **Beam trawl** | *Median*<br>*(IQR)* | 8.00 $^{c, d}$<br>(3.30) | 67.16 $^{e, i}$<br>(123.14) |
| **Longline** | *Median*<br>*(IQR)* | 7.40 $^{b}$<br>(1.90) | 22.39 $^{f, j,}$<br>(55.22) |
| **Pot** | *Median*<br>*(IQR)* | 7.20 $^{b, d}$<br>(1.60) | 20.90 $^{g, \imath, i, j, k}$<br>(60.07) |
| **Other** | *Median*<br>*(IQR)* | 7.25 $^{b}$<br>(2.20) | 44.78 $^{h, k}$<br>(70.15) |
| **Kruskal-Wallis Test** | | $\boldsymbol{p = 0.001}$ | $\boldsymbol{p = 0.001}$ |

$^{a, b, c, d, e, f, g, h, \imath, i, j, k}$ Superscripts indicate the difference between groups. There is no difference in the groups with the same letters.

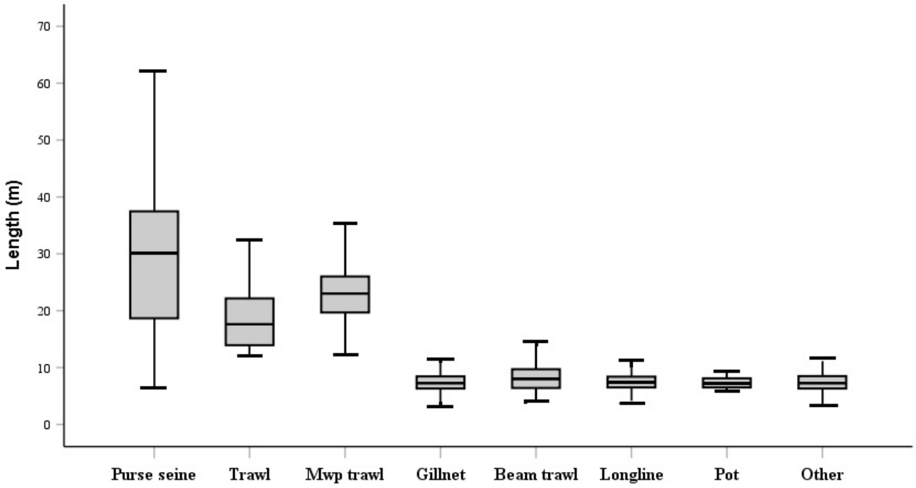

**Figure 1.** Comparison of length values according to fishing gear

It was determined that purse seines, mwp trawlers and trawlers had higher engine power values then other five fishing gear groups with statistically significant difference ($p$= 0.001). Among the five gear groups with median values between 20,9 and 67.2, a statistically significant difference was not found between pot and the other four gear groups ($p$>0.05) (Table 3 and Figure 2).

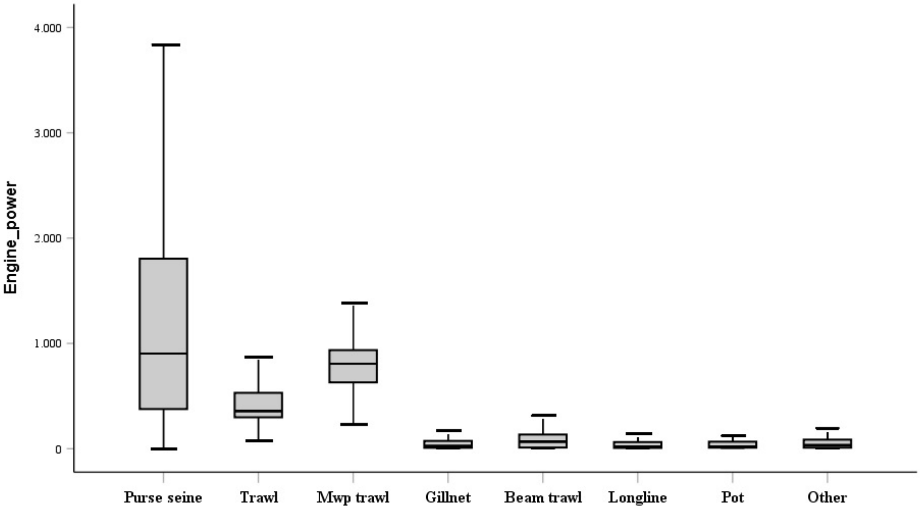

**Figure 2.** Comparison of engine power values according to fishing gear

## 3. CONCLUSION AND RECOMMENDATIONS

It was concluded that the findings on the construction of the Turkish marine fishing fleet in this chapter are consistent with the literature.

SSF in Türkiye is defined in the literature as "fishing carried out by fishing vessels smaller than 12 meters, which accept the coastal area as their fishing grounds, use passive fishing gear (gillnets, longlines, pots, etc.) for daily fishing, and sell their catch commercially" (Ünal, 2003; Ünal ve Ulman, 2020). In this chapter, the mean lengths (7.36-8.31 m) determined for beam trawl, gillnet, longline, pot and other vessels which constitute 95.5 per cent of the whole fleet, were smaller than 12 meters as defined above.

Purse seine, mid-water pelagic trawl and single boat bottom otter trawl vessels, defined as industrial fisheries or large-scale fisheries, had higher length and engine power values with a statistically significant difference ($p= 0.001$) than the other fishing gear groups using vessels under 12 m, defined as small-scale fisheries. Similarly, Tunca et al. (2021) reported the high associated costs of technological inputs, including gross tonnage, engine power, total generator power, lamp vessel generator power for the Turkish Aegean purse seine fleet.

Wood was dominant in SSF and sheet metal in LSF as construction material. However, due to lack of data, analyses regarding ages and construction locations could not be made in this chapter. In order to improve the future planning and sustainability of large-scale fisheries, which provide for 78.4% of Türkiye's marine fisheries production (GDFA, 2023), more detailed information (e.g., capacity, location) on the LSF shipbuilding industry is needed.

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# CHAPTER II

# AN OVERVIEW OF THE POTENTIAL OF ALTERNATIVE FUELS IN DECARBONIZING FUTURE SHIPPING

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## ABSTRACT

Currently, shipping is seen as the most effective mode of transportation in the world. Marine vessels are generally driven by fossil fuel – dependent marine diesel engines and thus, result in carbonization of the environment. International legislations require some strict emission limits for the ships in operation to achieve decarbonization targets for the future (2030 & 2050). One effective way to reduce greenhouse effect of shipping is to utilize alternative fuels in marine vessels. Therefore, this study aims to overview some recent works concerning the use of alternative fuels in ships to improve decarbonization. In this context, alternative fuels such as ammonia, hydrogen, methanol, liquefied natural gas (LNG) and dimethyl ether (DME) are examined. The advantages and disadvantages of utilizing those fuels in marine engine systems are explained. The potential of emission reduction in ships due to alternative fuels is extensively examined. Moreover, the challenges need to be overcome for practical operation are also presented for each aforementioned alternative fuel.

**Keywords**: Marine diesel engines, low-emission shipping, decarbonization, alternative fuels

## INTRODUCTION

Today, modern marine vessels are dominantly operated through internal combustion engines, particularly via diesel engines due to improved thermal efficiency, enhanced fuel economy and reliability. 4 stroke and 2 stroke marine diesel engines are the most common power units for propulsion in ships [Ni et al. (2020)]. While most of the large marine vessels such as containerships and tankers are propelled through 2-stroke marine diesel engines, small vessels such as fishing vessels and tugboats are driven by 4-stroke marine diesel engines. Unlike aforementioned commercial marine vessels, naval vessels are generally powered through steam or gas turbines or combination of diesel engines and gas turbine systems [Haglind (2008)].

Ships mostly utilize marine liquid fuels in order to meet the power need for the propulsion. Heavy fuel oil (HFO), marine diesel oil (MDO) and marine gas oil (MGO) are the most widely used fuels in marine vessels [Corbett (2004)]. The carbon content of those fuels is noticeably high. After combusted in marine power units, they result in high rates of $CO_2$ emission into the environment. Therefore, they highly increase the greenhouse effect through carbonization of the atmosphere [Hoang and Pham (2018)]. Also, the nitrogen oxide ($NO_x$) and sulphur oxide ($SO_x$) emissions due to aforementioned carbon-based fuels have some serious negative effects on human health and marine life, which is a significant concern for environmental agencies [Zhao et al. (2021)]. Thus, in addition to low $CO_2$ rate, low $NO_x$ & $SO_x$ rate is a must for ships too.

Faced with the inevitable rise of carbonization of ship transport, the International Maritime Organization (IMO) has issued some strategies to control it at a manageable level. IMO aims to halve the greenhouse gas (GHG) rates due to ships in 2050 compared to the levels in 2008. It also plans to decrease ship-dependent $CO_2$ emission rates by 40% in 2030 and by 70% in 2050 [Joung et al. (2020)]. Considering the current fossil fuel-dependency of shipping, those targets are highly strict and present some hard-to-deal with technical difficulties for the current and future shipowners. Therefore, there is a need to enhance the decarbonization and decrease the $NO_x$ and $SO_x$ rates of shipping in order to fulfill the stringent IMO regulations [Jimenez et al. (2022)]. Recently, replacing traditional fuel sources with alternative fuels is seen as a viable and promising technique to achieve this goal [Rony et al. (2023)].

This study focuses on the literature survey of several alternative fuels to decrease decarbonization in marine vessels. It should be kept in mind that using alternative fuels is one way to reduce carbonization. Improved hull design, optimization of transportation routes, optimizing marine vessel speed, using exhaust after-treatment systems can also be applied as effective emission reduction techniques [Balcombe et al. (2019)]. It is generally considered to implement alternative fuels in ships combined with those aforementioned methods to meet the strict 2030 and 2050 emission targets of IMO. However, alternative fuels have some serious challenges to deal with in order to maintain safe ship operations as well [Chiong et al. (2021)]. Thus, those disadvantages should be carefully evaluated before any short-term or long-term plan is prepared based on the replacement of fossil fuels with alternative fuels.

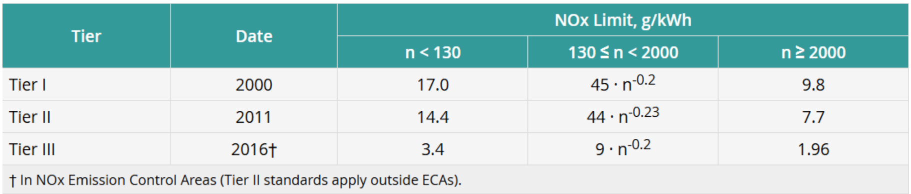
## 1. SHIP-RELATED EMISSIONS

In this section, current emission regulations on ships are explicitly explained. The methods for the control of exhaust-out emission rates in marine vessels are also briefly examined.

### 1.1. Emission limits

Similar to highway vehicles, marine vessels need high amounts of fresh air to combust HFO, MDO or MGO and maintain the steady operation in ports or open sea conditions. Since the lower heating value of those fuels is high, there is mostly high in-cylinder temperature during vessel operation, which results in high $NO_x$ production [Yang et al. (2012)]. Also, conventional marine fuels contain sulphur and thus, ships release considerable amount of $SO_x$ along their routes. $SO_x$ is not only harmful to human health, but also can affect the environment negatively through causing acid rains. Therefore, in order to avoid those adverse effects of those gases, IMO have set some strict limits for both $NO_x$ and $SO_x$ for ships in operation, as demonstrated explicitly in Table 1 and Table 2 below [Dieselnet (2024)].

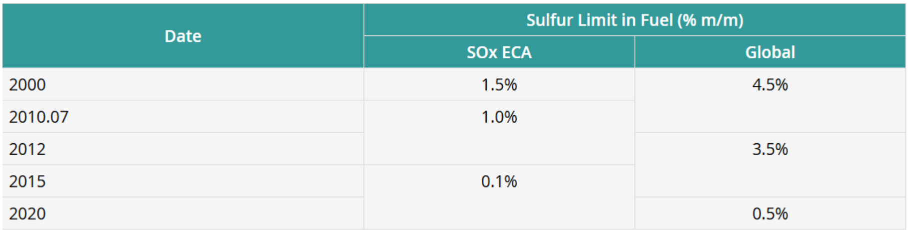
**Table 1:** Emission limits of $NO_x$ for ships [Dieselnet (2024)]



| Tier | Date | NOx Limit, g/kWh | | |
|---|---|---|---|---|
| | | $n < 130$ | $130 \le n < 2000$ | $n \ge 2000$ |
| Tier I | 2000 | 17.0 | $45 \cdot n^{-0.2}$ | 9.8 |
| Tier II | 2011 | 14.4 | $44 \cdot n^{-0.23}$ | 7.7 |
| Tier III | 2016† | 3.4 | $9 \cdot n^{-0.2}$ | 1.96 |

† In NOx Emission Control Areas (Tier II standards apply outside ECAs).

**Table 2:** Emission limits of $SO_x$ for ships [Dieselnet (2024)]



| Date | Sulfur Limit in Fuel (% m/m) | |
|---|---|---|
| | SOx ECA | Global |
| 2000 | 1.5% | 4.5% |
| 2010.07 | 1.0% | |
| 2012 | | 3.5% |
| 2015 | 0.1% | |
| 2020 | | 0.5% |

As stated in Table 1, starting from Tier 1, there is a constant demand by IMO for the reduction of $NO_x$ rates of ships Those limits are applied for ships with a power unit higher than 130 kW. Also, it is seen that different limits are valid for marine vessels with different engine maximum speed (seen as “n” in Table 1). Tier II is stricter than Tier I and is applied globally outside the emission control areas (ECAs). Inside the ECAs, ships are subject to Tier III, which has the most stringent $NO_x$ limits. In addition to those strict $NO_x$ limits, ships have to be controlled considering the $SO_x$ limits shown in Table 2. Global sulphur limit has been dramatically reduced since 2000. Current global sulphur limit is one ninth of that in 2000 (from 4.5% to 0.5%), which mainly drives innovative alternative fuels to be used for marine transport [Lee et al. (2024)]. The sulphur limit is even lower inside the ECA region (0.1%), which is challenging for marine vessels transporting cargo in that area. In the future, the global limits of $NO_x$ and $SO_x$ can be predicted to approach the limits in ECAs in order to achieve IMO’s 2050 emission goal. Therefore, ships constructed today and to operate in open water should be designed considering those highly diminished allowable emission limits. It is certain that shipbuilding need a serious long-term plan to meet IMO’s emission regulations and thus, to extend the operational life of ships [Eide et al. (2011)].

### 1.2. Emission reduction techniques

As mentioned in the previous subsection, it is highly demanding for ships to fulfill the all-time-low emission regulations. The current propulsion technology is heavily dependent on fossil fuel combustion in marine diesel engines and it is not expected to change radically in the medium term [Reitz et al. (2020)]. Electrification of ship propulsion can be successfully applied for some small marine vessels (such as fishing vessels, yachts etc.). However, it is still not as reliable as diesel engine-based propulsion and obviously it will require a long time to adjust this new battery-dependent technology to large commercial ships (such as ultra large crude carriers, Panamax tankers or containerships), which need considerably larger power units than that used in small electric vessels [Kistner et al. (2024)]. Therefore, improvement of current diesel technology is noticeably significant to attain the IMO's future emission goals and secure the marine transport in the following decade [Lion et al. (2020)].

One current and effective technology for the abatement of $NO_x$ from ships is to implement exhaust gas recirculation (EGR) in the engine system [Wang et al. (2017)]. $NO_x$ is heavily dependent on temperature and EGR can keep the in-cylinder temperature at low levels and thus, can enable decreased $NO_x$ rates. In addition to EGR, selective catalytic reduction (SCR) systems are widely utilized to reduce $NO_x$ rates [Chen et al. (2024)]. Control of exhaust temperature is significant to maintain effective SCR units in diesel engine systems [Basaran and Ozsoysal (2017)]. Other than SCR, Miller cycle can be used to maintain $NO_x$ rates at a desirable level [Wei et al. (2019), Basaran (2023)].

Researchers try to develop methods to curb $SO_x$ rates of marine diesel engines as well. One technique to control $SO_x$ emissions from ships is to utilize low sulphur fuel oil [Vedachalam et al. (2022)]. Another common method is to equip the ship with the scrubber systems to minimize the engine-out $SO_x$ rates [Tran (2017)]. Exhaust gas scrubbers placed downstream of marine diesel exhaust system are generally sufficient to meet strict $SO_x$ limits. However, those strategies generally increase the operational costs and are not seen as attractive solutions by shipowners. Thus, recently, renewable energy and renewable fuels in marine diesel engines are investigated as a potential alternative technique to sustain low-emission marine transport [Brynolf et al. (2022), Duranay (2024)].

In the following section, the effects of alternative fuels on the reduction of ship – related emissions are widely explored. Ammonia, hydrogen, methanol, liquefied natural gas (LNG) and dimethyl ether (DME) are primarily examined for the possible replacement of conventional fuels in ships. The disadvantages and drawbacks of those fuels that need to be overcome are also presented.

## 2. ALTERNATIVE FUELS FOR DECARBONIZATION

In this section, the effect of different alternative fuels on marine engine systems is examined. Not only the opportunities gained using those fuels, but also the setbacks for their practical application are analyzed. The potential of ammonia is explored first in the following subsection.

### 2.1. Ammonia

Ammonia ($NH_3$) is considered as a significant alternative fuel for ships. It can be provided from both fossil fuels and renewable energy sources, which is advantageous [Valera-Medina et al. (2018)]. Ammonia consists only of nitrogen and hydrogen and does not contain any carbon or sulphur. Thus, when used alone, it does not release any carbon oxides, unburned hydrocarbons (UHCs) or sulphur oxides, which is highly beneficial for the environment and meeting the strict emission legislations of IMO [Giddey et al. (2017)].

Ammonia mostly remains as a gas in ideal room temperature medium. In order to store and sustain high amounts of ammonia for high energy needs of heavy-duty vehicles and ships, it is needed to be liquefied. That is mostly achieved via cooling its temperature to low levels (below -33°C) or compressing it to pressures as high as 7.5 bar, which is costly compared to storage of the conventional marine fuels. Although ammonia performs better than hydrogen in terms of energy density ($MJ/m^3$), it is worse than LNG and methanol as seen in Figure 1 below [Marine Service Noord (2024)]. Admittedly, fuel storage area for ammonia will be lower than than for hydrogen, which is helpful to keep engine room relatively smaller and carry more cargo on the vessel. However, in comparison to LNG and methanol, for the same power need, using ammonia is not that advantageous as it requires higher fuel storage area and thus, lower space for the cargo, which is undesirable for the shipowners.

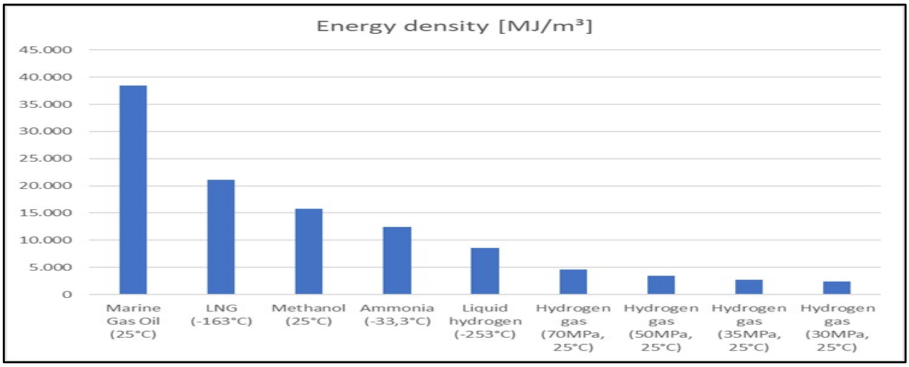


**Figure 1:** Energy density of different alternative fuels for the maritime sector [Marine Service Noord (2024)]

Ammonia necessitates rather high volumes for the fuel inside the marine vessels, which is disadvantageous in terms of profit. However, it can be stored as liquid in large tanks, the handling facilities of it are sufficiently developed and as a fuel, it can be directly utilized in current engine systems with minor modifications. Also, despite having lower energy density than marine gas oil, it can work at high compression ratios and improve the thermal efficiency as its octane number is rather high, which is desirable to compete with marine diesel engine systems. Thus, it has the potential to be an important alternative fuel in ships in the future [Dimitriou and Javaid (2020)]. Ammonia is flammable. But there is mostly a low fire risk due to a possible vapour leakage inside the ship since its combustion temperature (651°C) is rather high. Compared to ignition temperature of propane (432°C), another potential alternative fuel for marine vessels, it is much safer to use ammonia in ships [Herdzik (2021)].

One noticeable problem with ammonia is that it is toxic, affects human health negatively and in case of a major leak in the ocean, it can be a significant threat to marine life. Also, as its ignition temperature is high, it is prone to cause incomplete combustion and thus, may result in high $NH_3$ emissions into the surrounding, which is environmentally considerable [Kim et al. (2020)]. Another drawback of ammonia is its higher fuel expense compared to marine diesel oil [Zincir (2022)]. In the long term, as used widely, it can get cheaper and be available for many different commercial ships. However, in the short & medium terms, it seems that for marine vessels, the traditional fuel is more favourable in terms of cost. Moreover, ammonia elevates $NO_x$ and $N_2O$ emission rates as it includes high amount of nitrogen. In most cases, an aftertreatment system is needed to control $NO_x$ rate in the engine system, which requires additional cost [Xu et al. (2023)]. However, despite those disadvantages, it is a carbon-free fuel and thus, when used alone for the combustion, any release of $CO_2$, CO or UHCs is out of question, which enables ammonia as a strong candidate for the future alternative fuel of shipping [McKinlay et al. (2021)].

### 2.2. Hydrogen

Another alternative fuel to reduce ship-related GHGs in marine transport is to use hydrogen. In fact, hydrogen is considered as one of the most promising alternative fuels for next-generation internal combustion engines [Onorati et al. (2022)]. The only emission with hydrogen alone combustion is water vapour, which does not allow any $CO_2$ emissions and is in line with IMO's 2050 decarbonization target for ships [Mahía Prados et al. (2024)]. Thus, it has the potential to provide carbon-free and sulphur-free mobility of highway vehicles and marine vessels in the coming decades.

One advantage of hydrogen is that it can be produced from many different sources (e.g. electrolysis of water) and can be applied not only in spark-ignition or dual-fuel engines, but also in fuel cells, which can ensure its widespread usage for ships in the future [Bouman et al. (2017)]. Also, it is possible to store hydrogen fuel for long-distance transport in large volumes, which is necessary to meet the energy needs of commercial ships navigating the oceans. Another benefit of hydrogen is that it does not involve any carbon content and can ensure non-$CO_2$.operation of engine systems or fuel cells in marine vessels, which is favourable in comparison to methanol, ethanol, LNG and DME [Wang et al. (2024)]. Some of the opportunities and challenges of hydrogen utilization for transportation are explicitly shown in Figure 2 below [Le et al. (2024)].

**Figure 2:** Challenges and opportunities in the hydrogen sector [Le et al. (2024)]

Hydrogen is considered as a clean fuel and enables $CO_2$-free operation. However, there are some serious challenges to deal with to ascertain the practical use of hydrogen in marine vessels as well. One of those challenges is that hydrogen has a very low density (0.0905 kg/m$^3$) in its gas form and needs to be stored as liquid form during vessel operation. That is mostly achieved through insulated cryogenic storage tanks, which results in increased capital cost [Qiu et al. (2021)]. Moreover, the critical temperature of hydrogen is too low (-240$^o$C), which makes it even more difficult and costly for its liquid storage in ships. Methane, another possible marine fuel, is advantageous compared to hydrogen in terms of fuel storage cost since its critical temperature (-82.45$^o$C) is relatively high. However, in terms of environmental cost, hydrogen is superior to methane as it allows zero-carbon emissions [Lin et al. (2023)]. Despite better environmental performance, hydrogen is still a high-cost fuel and its current infrastructure is required to be improved. For hydrogen to be considered as a feasible alternative fuel for future shipping, some significant improvements are needed, such as provision of fuel production facilities close to ports, ensuring sufficient number of refueling stations for the ships and regulating its storage and handling for safe marine transport [Kim et al. (2023)].

### 2.3. Methanol

An effective solution to decrease the ship-related GHG emissions is to use methanol for the energy need of marine vessels [Fridell et al. (2021)]. Methanol is the simplest alcohol and has the chemical formula of $CH_3OH$. It is colourless, has a distinguished smell and can be produced from natural gas and renewable electricity, which is useful to improve emission rates [del Pozo et al. (2022)].

One advantage of methanol is that it can be utilized in gasoline engines as well as in diesel engines. While it is effective for premixed combustion in spark-ignition engines, it is generally used with an ignition source in compression-ignition engines [Zhen and Wang (2015)]. Blended use of methanol with diesel fuel can also be implemented in diesel engines. Those dual-fuel diesel engine operations have the potential to decrease $NO_x$, CO and soot rates [Saxena et al. (2021)]. However, a diesel-methanol dual-fuel engine generally requires two separate fuel pumps and injectors. The low lubricity and viscosity of methanol necessitates an advanced injection system, which can be challenging and costly for future dual-fuel marine engines [Curran et al. (2024)]. Another advantage of methanol is that it does not consist of any sulphur content and thus, can meet the stringent $SO_x$ regulations of IMO. That is favourable compared to conventional $SO_x$ – producing MDO or MGO used in ships. Also, methanol can be maintained as liquid form at room temperature and pressure, which enables its bunkering operation relatively less complicated compared to natural gas or hydrogen. The supply chain of methanol is not predicted to be faced with major difficulties, albeit some minor economic barriers. Thus, methanol is considered as a technically practical alternative fuel for the dearbonization of future shipping [Svanberg et al. (2018)].

Despite the advantages mentioned above, methanol has some disadvantages as well. One of its disadvantage is the lower energy density compared to diesel fuel. The lower heating value of methanol is 20 MJ/kg, which can be only half as much as diesel fuel (42-46 MJ/kg). Therefore, fuel storage area on methanol – fueled ships need to be more than doubled so as to provide the required power and maintain the reliable transport of cargo for long routes [Karvounis et al. (2023)]. Similar to ammonia and hydrogen, methanol-dependent marine vessels may need to place lower space for cargo, which decreases the maximum profit and can be deterring for most shipowners. Another disadvantage of methanol is its low flash point (11 to 12°C), which needs higher safety measures for the storage compared to diesel fuel [Parris et al. (2024)]. Also, although it is miscible with water and its concentration does not exceed to hazardaous levels in case of a spill, it is toxic and can have some serious local effects in the environment during an uncontrolled leakage [Brynolf et al. (2014)].

A carbon emission-free ship was achieved in HyMethShip Project, which uses the system demonstrated in Figure 3 [Zelenka et al. (2019)]. The system developed utilizes not only renewable methanol but also a combustion engine fueled with hydrogen. Methanol, preserved in methanol tank on the ship, is resolved to hydrogen after passing through the $CO_2$ capture system, which directs the remaining $CO_2$ into $CO_2$ storage tank. Those stored $CO_2$ can be used on-shore to produce renewable methanol, which is then used back on the ship for the propulsion energy, causing a noticeable $CO_2$ reduction. The HyMethship project shows that combination of renewable methanol, $CO_2$ capture and storage systems and a hydrogen-dependent combustion engine can be a feasible way to maintain $CO_2$-free shipping in the coming decades.

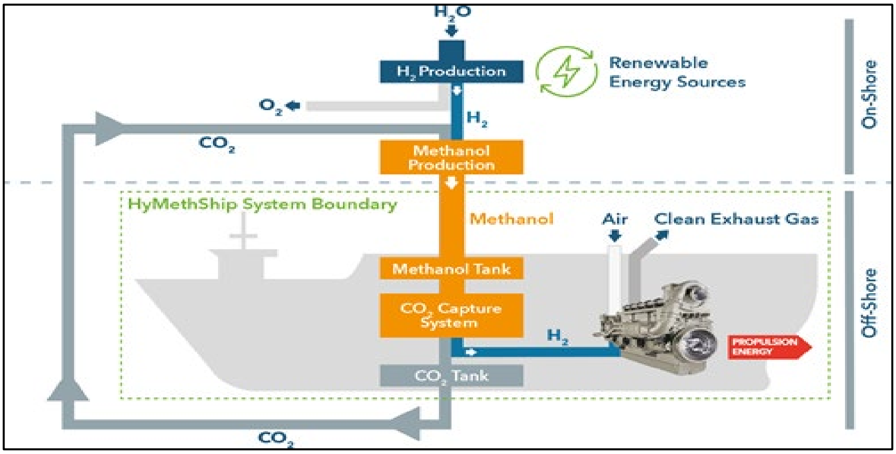


**Figure 3:** HyMethShip concept [Zelenka et al. (2019)]

## 2.4. Dimethly Ether (DME)

DME has a formula of $CH_3OCH_3$ and remains as a gas form at standard pressure and temperature condition (due to boiling temperature of -25°C) [Takeishi (2016)]. It is colourless at ideal room temperature, can be yielded from many different carbon-dependent materials and can be utilized in diesel engines [Park and Lee (2014)].

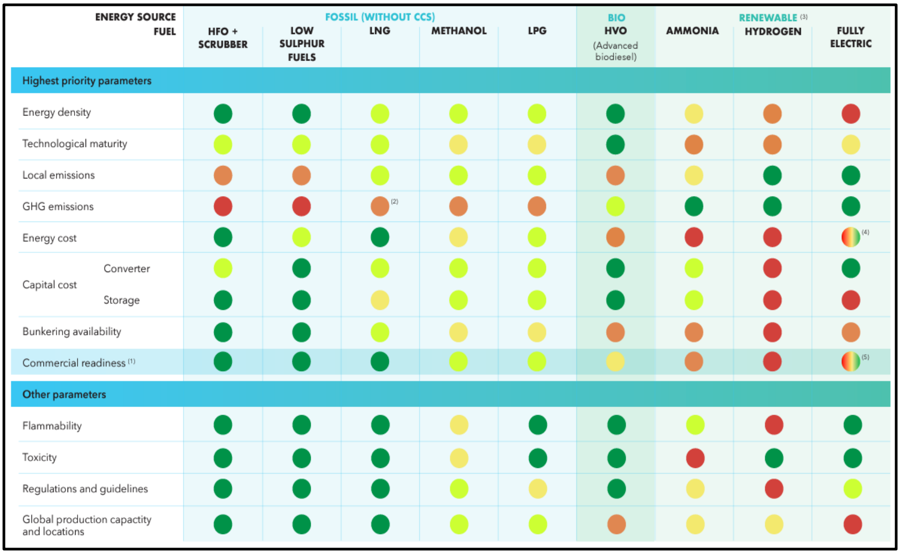
One advantage of utilizing DME in ships is that it is non-toxic and thus, does not pose any threat to ocean life when there is any possible leakage into the environment. Moreover, since it is a sulphur-free fuel, it does not release any $SO_X$ or PM, which is compatible with strict $SO_x$ regulations of IMO. Thus, DME can be a replacement for low-sulphur MGO in ships [Thomas et al. (2014)]. It is possible to reduce CO rates in diesel engines using DME as well [Park and Lee (2013)]. Unlike diesel fuel, DME does not involve carbon-carbon bonds and is therefore not prone to produce high soot rates, which is environmentally advantageous. It is not as expensive as natural gas and other possible alternative gaseous fuels, which can be helpful to improve fuel consumption cost in ships [Korberg et al. (2021)].

DME owns some significant challenges although it is effective to reduce $CO_2$, $SO_x$ and PM rates in ships. Significant modulation in current diesel engines is required for the practical use of DME in highway vehicles and marine vessels. A particular fuel pump or a particular injector is generally needed for the operation of a DME-based diesel engine, which rises the production costs [Astbury (2008)]. As its lower heating value is lower compared to that of MDE, higher fuel storage space should generally be arranged in ships in order to maintain the vessel's energy need and attain the similar useful propulsive power. That may probably lead to smaller space for cargo and reduce the profit for the commercial ships, which discourages most of the shipowners. The low viscosity and high flammability of DME are also considerable challenges [Zhang et al. (2014)], which can be a serious threat to sustain safe and reliable operation in marine vessels. Overall, DME is not the first choice for marine vessels at present due to its undesirable properties mentioned above. However, it has a potential to reduce particularly $CO_2$ and $SO_X$ rates in marine vessels. Thus, as its infrastructure is improved and its production is adequately increased, it can be preferred as an alternative fuel (as main or auxiliary fuel) by the shipowners in the future [Soltic et al. (2024)].

### 2.5. Liquefied Natural Gas (LNG)

One other alternative for the replacement of conventional marine fuels is to use LNG in ships. LNG is mainly made up of methane and similar to hydrogen, it is required to be cooled to very low temperatures (as low as -162°C) for liquefaction and practical storage during long routes of commercial vessels [Sharma et al. (2022)]. Particular insulated tanks are needed to be installed on the ship to maintain the liquefaction of the gas. Those cryogenic tanks are effective to reduce the fuel storage space and increase the cargo holds in the marine vessel. However, they result in higher cost in terms of storage and handling than conventional HFO, MDF or MGO [Elgohary et al. (2015)].

LNG carriers have been using LNG as fuel for nearly 50 years. This demonstrates that the use of LNG in maritime transportation dates back to the 1970s and is therefore not new. After the 2000s, as the internal combustion engines are improved to use LNG as the main energy provider, a higher number of ships started to use LNG for transportation, which actually highlights its significance compared to other alternative fuels [Wang and Notteboom (2014)]. Despite the technological experience of its long usage in shipping industry, it is noted that LNG (chiefly methane, $CH_4$) is a carbon-dependent fuel and thus, has a restricted potential (compared to ammonia-, hydrogen- or battery-powered ships) to decrease $CO_2$ rates due to shipping. However, it does not contain sulphur, eliminates $SO_x$ emissions and has the potential to reduce $NO_x$ rates to low levels. More importantly, as seen in Figure 4, its bunkering availability and commercial readiness is superior to other alternative fuels, which may offer a long-term pathway towards zero-emission shipping [Sea-lng ltd (2020)].



| ENERGY SOURCE | FOSSIL (WITHOUT CCS) | | | | | BIO | RENEWABLE (3) | | |
|---|---|---|---|---|---|---|---|---|---|
| FUEL | HFO + SCRUBBER | LOW SULPHUR FUELS | LNG | METHANOL | LPG | HVO (Advanced biodiesel) | AMMONIA | HYDROGEN | FULLY ELECTRIC |
| **Highest priority parameters** | | | | | | | | | |
| Energy density | 🟢 | 🟢 | 🟩 | 🟩 | 🟩 | 🟢 | 🟡 | 🟠 | 🔴 |
| Technological maturity | 🟩 | 🟩 | 🟩 | 🟡 | 🟡 | 🟢 | 🟠 | 🟠 | 🟡 |
| Local emissions | 🟠 | 🟠 | 🟩 | 🟩 | 🟩 | 🟠 | 🟡 | 🟢 | 🟢 |
| GHG emissions | 🔴 | 🔴 | 🟠 (2) | 🟠 | 🟠 | 🟩 | 🟢 | 🟢 | 🟢 |
| Energy cost | 🟢 | 🟩 | 🟢 | 🟡 | 🟩 | 🟠 | 🔴 | 🔴 | 🔴🟡🟢 (4) |
| Capital cost Converter | 🟩 | 🟢 | 🟩 | 🟩 | 🟩 | 🟢 | 🟩 | 🔴 | 🟢 |
| Capital cost Storage | 🟢 | 🟢 | 🟡 | 🟩 | 🟩 | 🟢 | 🟩 | 🔴 | 🔴 |
| Bunkering availability | 🟢 | 🟢 | 🟩 | 🟡 | 🟡 | 🟠 | 🟠 | 🔴 | 🟠 |
| Commercial readiness (1) | 🟢 | 🟢 | 🟢 | 🟩 | 🟩 | 🟡 | 🟠 | 🔴 | 🔴🟡🟢 (5) |
| **Other parameters** | | | | | | | | | |
| Flammability | 🟢 | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 | 🟩 | 🔴 | 🟢 |
| Toxicity | 🟢 | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 | 🔴 | 🟢 | 🟢 |
| Regulations and guidelines | 🟢 | 🟢 | 🟢 | 🟩 | 🟡 | 🟢 | 🟡 | 🔴 | 🟩 |
| Global production capacity and locations | 🟢 | 🟢 | 🟢 | 🟩 | 🟩 | 🟠 | 🟡 | 🟡 | 🔴 |

**Figure 4:** Comparison of LNG with other alternative fuels [Sea-lng ltd (2020)]

The energy density of LNG is lower than HFO and low-sulphur fuels. However, it is higher than hydrogen and ammonia, which enables lower fuel storage space and thus, greater space for cargo holds compared to those alternative fuels. Although local emissions and GHG emissions due to LNG are not improved as much as with ammonia – fueled, hydrogen – fueled or fully electric ships, technological maturity and energy cost of LNG is better than almost all possible alternative fuels [Petrychenko and Levinskyi (2024)].

Another advantage of LNG is that, unlike methanol and ammonia, it is non-toxic, can be provided abundantly at a low price and compared to hydrogen, its capital cost for fuel storage is better. As shown in Figure 5, it is estimated that use of LNG fuel in ships will steadily increase until 2050 [DNV GL (2019)]. As predicted, use of conventional fuels, low sulphur fuel oil (LSFO) and MGO, is minimized in 2050 in maritime transport. Particularly ammonia is predicted to play an important role in marine vessels after 2040. However, LNG stands out as the most favourable alternative fuel in 2050 due to aforementioned enhanced priority parameters compared to other alternative fuels stated in Figure 4.

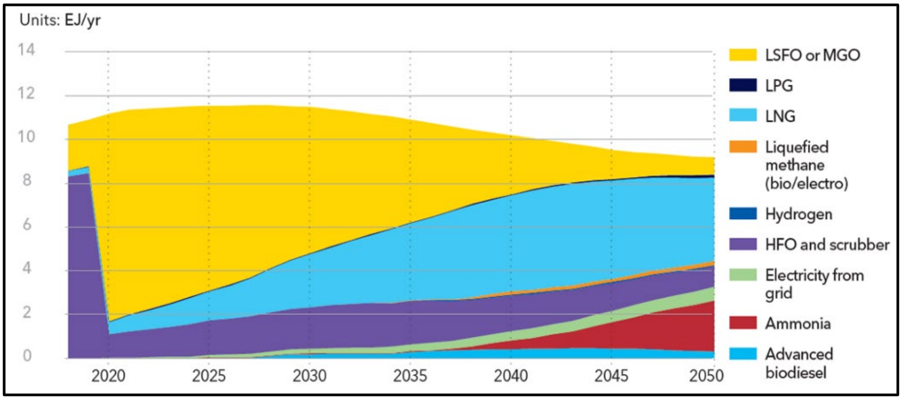


**Figure 5:** Energy use and projected fuel mix 2018-2050 for the simulated IMO ambitions pathway with main focus on design requirements [DNV GL (2019)]

LNG appears to be the most promising alternative fuel for shipping in the run-up to 2050. However, some challenges need to be overcome before this goal is achieved. One significant disadvantage of LNG-fueled ships is the methane leakage, which is regarded as an important GHG by environmental agencies [Kuittinen et al. (2024)]. In order to reduce the negative effect on the climate, methane leakage should be thoroughly controlled and thus, minimized. Improved combustion mixture, decreasing the cracks in the system and developing advanced combustion chambers are some of the techniques to achieve low methane leakage in LNG ships [Lehtoranta et al. (2021)]. Although those methods are effective to diminish methane leakage, they also require frequent maintenance and thus, increases the operation cost of the engine systems. Another disadvantage of LNG is the need of cryogenic tanks for its storage, which is not an issue for current HFO or low sulphur fuels in ships. Therefore, during the transition to LNG-fueled ships, the high cost resulting from the need to preserve LNG at low temperatures should be considered by the shipowners. Also, energy density of LNG is lower than HFO, which requires larger fuel tanks and modulation of the engine room. Finally, the supply infrastructure of LNG is still inadequate for a full transition from MDF, HFO and MGO – based to LNG – based marine transport [Pfoser et al. (2018)].

## CONCLUSIONS

This study aims to overview the potential of alternative fuels on the reduction of ship-related carbonization. Marine diesel engines will continue to be used as the prime mover in ships in the coming future. Therefore, utilizing low-carbon alternative fuels can be an effective solution in the short and medium term to improve decarbonization of ships. In the long term, alternative fuels can be combined with advanced combustion techniques and after-treatment systems such as SCR to further decrease criteria pollutants and thus, meet IMO's stringent emission regulations.

Ammonia, hydrogen, methanol, DME and LNG are examined as possible alternative fuels in maritime transport in this work. Ammonia is seen to be a favourable fuel in marine vessels as it does not contain any carbon content and thereby, not allowing any $CO_2$ emissions after combustion. However, it involves high nitrogen content and increases $NO_x$ rates, which is undesirable. Moreover, its energy density is lower compared to traditional fuels and thus, needs higher space for fuel storage and lower space for cargo, which reduces the profit. Similar to ammonia, hydrogen does not include any carbon content and thus, minimizes $CO_2$ rates in ships. However, its storage requires additional equipment and is more expensive compared to conventional marine fuels. Also, its infrastructure is still insufficient to achieve a complete shift from MDF- or MGO – dependent shipping to hydrogen-dependent shipping. Unlike ammonia and hydrogen, methanol has high energy density, requires lower storage cost and can allow higher space for cargo holds in ships. However, it is toxic, can have negative effect on the environment in case of a large spill and requires additional safety measures due to low flash point. Unlike methanol, DME is non-toxic. It does not contain any sulphur content, which minimizes SOx rates. However, it needs some complex modulation in the engine systems to safely combust DME in ships. Its lower heating value compared to MDF is another disadvantage, which requires high rates of DME consumption to maintain similar engine power in ships. Among all alternative fuels, LNG is found to be the most promising as it has high energy density, relatively improved infrastructure and bunkering systems, is technologically more mature, less toxic and its safety regulations are already developed. Despite high storage cost, LNG is seen to be the best transit fuel before fully-electric or hydrogen-dependent shipping is maintained for long ocean-going routes in the future.

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# CHAPTER III

# POLLUTANTS FROM SHIPBREAKING: ENVIRONMENTAL IMPACTS AND RISK MANAGEMENT

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## Abstract

Increasing world population has led to a rise in the speed of production to meet human needs. To achieve this, faster and more advanced technologies are now being utilized. However, increased production also results in the degradation of natural resources. As humanity and technology advance, many critical ecosystems vital to the planet are being damaged. To address this, the concepts of "sustainable development" and "sustainable environment" have emerged as central topics for humanity. Recycling technologies are among the strongest proponents of this sustainability paradigm. A significant portion of global trade is conducted via maritime transportation. Recycling ships that have reached the end of their service life and reusing materials obtained from decommissioned vessels in industrial production offer both economic benefits and reductions in the energy required to produce these materials from scratch. This indirectly mitigates environmental degradation. However, if the ship recycling process is conducted without necessary precautions, it can pose significant environmental risks. Nearly all parts and equipment of a ship, particularly its hull, contain highly toxic substances harmful to humans and the environment. In leading shipbreaking countries like Bangladesh, India, and Pakistan, the dismantling process has historically been performed through beaching methods. This practice has led to the dispersal of waste into sediments, soil, and water, causing extensive pollution. Environmental studies conducted at shipbreaking facilities worldwide have revealed contamination levels far exceeding baseline values in these areas. Since the late 1980s, international regulatory efforts have been underway, and many shipbreaking nations have begun to adopt these regulations. Ship recycling activities carried out in accordance with these established standards are expected to contribute to environmental protection while also supporting economic development.

**Key words:** Shipbreaking, Marine pollution, Hazardous materials

## The Importance and History of Shipbreaking

Commercial vessels operating in the seas transport over 80% of global trade goods by volume and serve as one of the primary components regulating the world’s socio-economic metabolism (Rabbi & Rahman, 2017; Lin et al., 2022).

The service life of a ship is typically considered to be around thirty years, and due to increasing maintenance costs, hundreds of ships are decommissioned annually. Aging and retired vessels contain significant quantities of valuable materials. It is a more rational approach to recycle these materials rather than leaving them to decay unused (Rabbi & Rahman, 2017; Lin et al., 2022). For this reason, ships are subjected to recycling processes, with shipbreaking forming the backbone of this industry. Shipbreaking is a challenging process carried out at docks, dry docks, or dismantling yards. It begins with the removal of all equipment and machinery and extends to the cutting of the ship's structural components (Yahya et al., 2012). To provide an idea of the scale of shipbreaking activities, statistics indicate that in 2019, the number of ocean-going ships sent for dismantling exceeded 800 (Lin et al., 2022), compared to approximately 700 in 2002, representing about 1.55% of the total active ocean-going fleet (Hossain & Rahman, 2010). During the global economic crisis of 2008-2009, excess capacity led to a significant increase in the number of vessels dismantled (Rabbi et al., 2017). According to 2020 statistics, 5.8 million tons of steel are recycled annually from shipbreaking activities (Rizvi et al., 2020).

The energy savings and reduction in carbon dioxide emissions from recycling are considerable. Producing steel from hematite ore consumes 7,400 MJ of energy and emits 2,200 kg of carbon dioxide per ton, whereas steel production from scrap requires only 1,350 MJ of energy and results in 280 kg of carbon dioxide emissions (Neşer et al., 2008). From this perspective, ship recycling offers significant advantages in resource utilization. Moreover, the reduction in mining activities due to shipbreaking goes beyond energy conservation, contributing to a substantial decrease in environmental damage. In addition to reducing the need for imported steel, shipbreaking activities play a significant role in the economy by creating employment opportunities. Thousands of workers benefit from these economic opportunities, and regions requiring private sector investment gain significant advantages for growth (Hossain & Rahman, 2010).  For example, in Bangladesh, over 25,000 people are directly employed in shipbreaking, while more than 200,000 are engaged in related industries (Siddiquee et al., 2012). From an economic perspective, shipbreaking is considered an efficient and highly profitable industry.

Until the 1960s, the shipbreaking sector was dominated by developed countries such as the United States, the United Kingdom, Germany, and Italy. Notably, the UK conducted 50% of global shipbreaking activities in Scotland (Hossain et al., 2016). However, during the 1970s, the industry began shifting from Europe to Asia, initially relocating to Taiwan and South Korea (Hossain et al., 2016; Karim, 2010). By the 1980s, to maximize profits, the industry moved to countries with cheaper labor such as India, Pakistan, the Philippines, China, Vietnam, and Bangladesh (Hossain & Rahman, 2010).

According to 2017 statistics, although shipbreaking/recycling activities are carried out in 82 countries worldwide, 97-98% of the global tonnage is handled in Bangladesh, India, Pakistan, China, and Turkey (Kurt et al., 2017; Rizvi et al., 2020). This shift from Europe to Asia was influenced not only by the appeal of lower labor costs but also by stricter environmental regulations in Europe and comparatively lax regulations in Asia, as well as fewer responsibilities regarding occupational safety in Asian countries (Hossain & Rahman, 2010; Karim, 2010; Hossain et al., 2016).

In the 1970s, OECD countries began implementing environmental measures that increased the costs of industrial hazardous waste disposal and management (Kutub et al., 2017). This development created new avenues for the disposal of hazardous waste, and a new market emerged in South Asia (Kutub et al., 2017). India and Bangladesh have become leading nations in the global shipbreaking industry. Although India lost its leadership position to Bangladesh between 2004 and 2008, it regained the lead from 2009 to 2011. Nevertheless, Bangladesh's increasing prominence in the sector since 2002 is evident (Hossain et al., 2016).

Despite the economic advantages offered by Far Eastern countries, Turkey presents more favorable conditions for European countries due to its geographical location (Neşer et al., 2008; Yılmaz et al., 2016) The history of shipbreaking in Turkey dates back several decades. Before 1976, lightweight ships were dismantled at a state-owned shipyard located in the Golden Horn and approximately 100 km from Istanbul. Since 1976, shipbreaking activities in Turkey have been carried out in Aliağa, located on the Aegean coast (Figure 1). A significant portion of Turkey's scrap iron demand is met by this facility (Neşer et al., 2008).

Figure 1. The Aliağa shipbreaking facility on the coast of Aegean Sea.

## The Shipbreaking Process

The shipbreaking process typically occurs on beaches along coastal areas, where pollutants from dismantled ships often seep into the environment (Siddiquee et al., 2012). Rizvi et al., (2020) summarize the shipbreaking process as follows: The beaching method is regarded as the most hazardous among shipbreaking techniques. It poses severe risks to both the environment and human health. This method is generally employed in coastal areas with expansive sandy and muddy flats. Ships anchored offshore are stripped of removable components, making them lighter. Subsequently, the ship is hauled onto the beach using cranes, facilitating easier dismantling. Before cutting begins, interior panels, furniture, electrical and electronic systems/devices, and decorative materials are removed and sold in local markets (Figure 2). Workers then use gas-cutting torches to divide the ship into plates and blocks. These dislodged plates fall onto the beach and are transported for disposal. Some materials are sent to factories, while others are reused in shipyards for repair and renewal work.

While materials recovered from this process are repurposed, the ship hulls are often discarded in ship graveyards. In Bangladesh, the shipbreaking industry supplies 90% of the country’s iron and steel needs(Hossain et al., 2016).

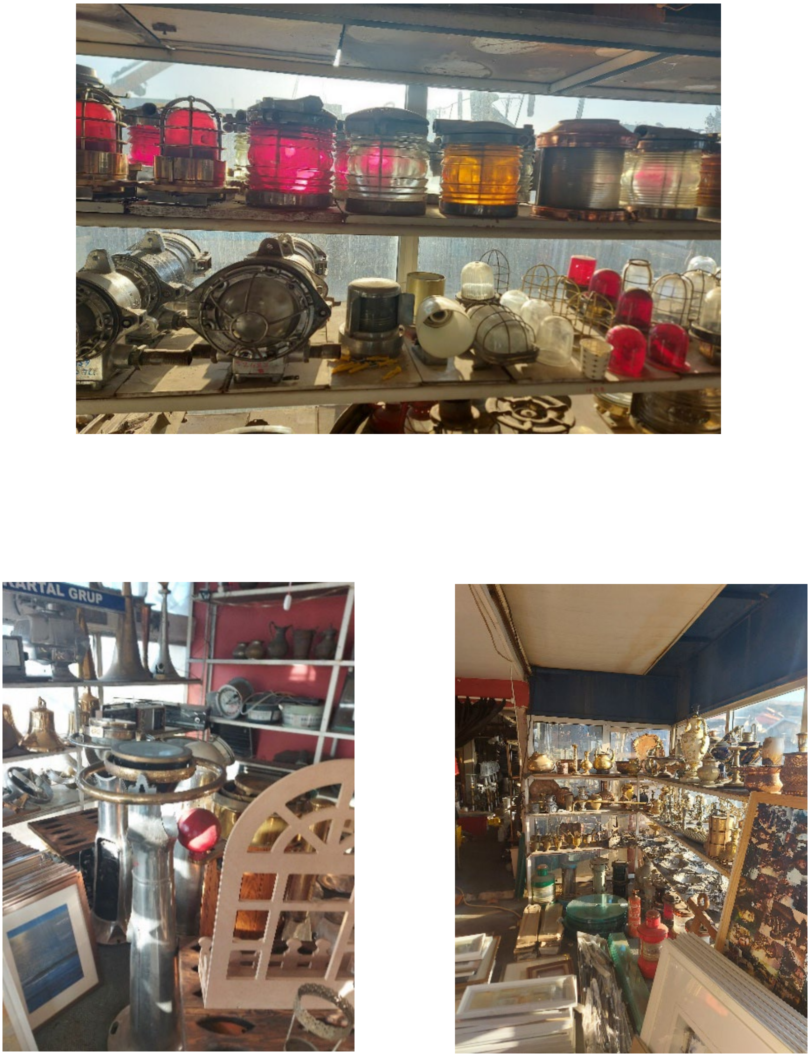

Figure 2. A local shop in Aliağa selling accessories from shipbreaking facility.

The rapid growth and profitability of this industry in Bangladesh and similar countries are partly attributable to weak environmental regulations. For example, in the beaching method, ships dismantled on the beach release substances such as asbestos, oil residues, and toxic metals into the ocean (Kakar et al., 2021).

The following figures are striking in providing an idea of the amount of materials entering the ocean: According to a 2010 report by the World Bank, military and civilian ships are estimated to contain approximately 44 and 75 kg of mercury per million gross tons, respectively ( Sarraf et al., 2010; Kakar et al., 2021).

It is reported that 70-80% of the world's ships are dismantled in India, Pakistan, and Bangladesh using this method (Lin et al., 2022; Sarraf et al., 2010). When examining the origins of the ships dismantled in 2019, they were predominantly from the EU (20.03%), South Korea (8.22%), the USA (6.76%), Japan (6.43%), and China (6.33%). Bangladesh had the largest share in terms of volume. India and Turkey followed Bangladesh in terms of tonnage, with these ships originating from the EU, USA, and Norway. Since China imposed a ban on dismantling imported ships, it has been dismantling only its domestic vessels. Pakistan, on the other hand, mainly dismantles ships originating from the EU and Arab countries. In terms of ship tonnage, Turkey and the EU dismantle smaller vessels, whereas China, India, Pakistan, and Bangladesh handle larger ships (Lin et al., 2022). Neşer et al., (2008) state that the shipbreaking method used in Aliağa is not the beaching method, which poses significant risks to the environment and human health. Instead, a "modified slipway recycling" method is employed. In this technique, ships are pulled ashore, cut into large pieces, and then these pieces are transported inland. Smaller parts are processed in designated areas.

## Pollutant Sources and Environmental Impacts of Shipbreaking Facilities

Coastal areas serve as transitional zones between terrestrial and marine ecosystems. These regions, often where rivers discharge into the sea, are nutrient-rich and therefore highly productive, supporting significant biodiversity. However, due to their role as interfaces between land and sea, coastal areas are heavily influenced by terrestrial activities, including riverine discharges and domestic or industrial waste.

Shipbreaking facilities, which operate directly in coastal regions, have a significant impact on coastal ecosystems. Although recycling is a cornerstone of sustainable development, shipbreaking, in particular, raises substantial environmental concerns. To better understand the magnitude of these concerns, consider the following statistics: ships are typically coated with 10 to 100 tons of paint that may contain substances such as lead, cadmium, organotins, arsenic, zinc, and chromium. Additionally, ships often carry hazardous wastes such as PCB-containing fillers, up to 7.5 tons of various types of asbestos, and thousands of liters of oils, including engine, bilge, hydraulic, and lubricating oils. Tankers, in particular, may contain up to 1,000 cubic meters of residual oil, while exhaust pipe gaskets can contain 250 grams of asbestos per layer, and a single battery unit may contain 6 kilograms of lead (Hossain & Rahman, 2010; Rizvi et al., 2020).

The presence of such large quantities of diverse pollutants highlights the significant risks that ship recycling poses to coastal and marine ecosystems. Furthermore, shipbreaking activities do not only harm the environment but also adversely affect workers' health. These workers, often operating under poor conditions, are exposed to and inhale toxic materials, which have severe health consequences (Devault et al., 2017; Rizvi et al., 2020).

Given that the shipbreaking process typically takes two to three months, it is evident that a substantial amount of waste is generated during this period (Lin et al., 2022). Below is a summary of various chemical groups found in ships, their high concentrations in shipbreaking areas, and their impacts on both the environment and human health:

### Persistent Organic Pollutants (POPs)

POPs are highly toxic compounds that do not naturally degrade in the environment. They accumulate in living tissues, particularly in fatty tissues, posing significant risks to humans, animals, and ecosystems. POPs are linked to cancer and endocrine system disorders ( Hossain & Rahman, 2010).

### Dioxins

Dioxins are byproducts of PVC and PCB production or incineration and are extremely toxic to human health. Exposure to dioxins significantly increases cancer risk (Hossain & Rahman, 2010).

### Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are organic pollutants composed of multiple aromatic rings of carbon and hydrogen (Barua et al., 2024). They are primarily associated with petroleum and its derivatives. PAHs are released during torch cutting, from burning paints, or when various wastes are intentionally incinerated. Oils leaking from ships during dismantling and mixing into seawater contribute to pollution and threaten biodiversity (Hossain et al., 2016). Petroleum not only causes chemical damage but also adheres to marine organisms, leading to death, and prevents fish eggs from hatching (Yahya et al., 2012). Additionally, oil interferes with water-atmosphere interactions, disrupting gas exchange. Low-molecular-weight PAHs typically cause acute poisoning, while high-molecular-weight PAHs exhibit carcinogenic effects (Barua et al., 2024; Witt, 1995). PAHs have been associated with lung, stomach, intestinal, and skin cancers, as well as DNA mutations (Hossain et al., 2016; Yahya et al., 2012).

### Polychlorinated Biphenyls (PCBs)

PCBs are highly toxic and persistent pollutants used as insulating materials in various ship systems. They are linked to cancer and diseases of the reproductive, nervous, liver, and immune systems (Hossain et al., 2016; Rizvi et al., 2020). PCBs exist in both solid and liquid forms and bioaccumulate within food chains, reaching higher trophic levels (Yahya et al., 2012). Despite being banned since the 1970s, PCBs are still present in many components of older ships (Yılmaz et al., 2016).

### Polyvinyl Chloride (PVC)

Many ship components are manufactured using PVC, a material with significant potential risks at every stage of its lifecycle—from production to disposal. Incinerating PVC during disposal is unsafe and costly, while burying it can lead to soil and water pollution (Yahya et al., 2012).

### Organotins

Organotins are a group of highly toxic chemicals released during shipbreaking. One of the most notable examples is tributyltin, commonly used in antifouling paints. Organotins can damage the nervous system, disrupt endocrine functions, and impair immune system responses (Hossain et al., 2016).

### Asbestos

Asbestos is used in ships for thermal or sound insulation. During ship dismantling, if safety precautions are not implemented, workers are exposed to it. Structurally, asbestos comprises long, silky fibers (Hossain et al., 2016) 2016). These fibers become airborne during shipbreaking and can be inhaled, reaching the lungs and causing severe respiratory diseases and cancer (Hossain & Rahman, 2010). Prolonged asbestos exposure is associated with lung cancer, mesothelioma, gastrointestinal cancers, and a condition known as asbestosis, characterized by lung fibrosis (Rizvi et al., 2020). These fibers may remain in the lungs before diseases manifest, eventually forming scar-like tissues that impair lung elasticity, making breathing increasingly difficult (Rizvi et al., 2020; Yahya et al., 2012).

## Heavy Metals

The accumulation of heavy metals in nature is a significant concern due to their high toxicity, inability to degrade biologically, and tendency to concentrate in coastal waters (Siddiquee et al., 2012). Heavy metals often adhere to particulate matter, settling into sediment where they accumulate. Under favorable chemical conditions, these metals can be re-released into the water and bioaccumulate in aquatic organisms (Çevik et al., 2009; Islam et al., 2013; Wang et al., 2012).

Heavy metals are commonly found in paints and electrical equipment used on ships. Fluorescent lights, thermometers, batteries, electrical switches, fire detectors, and lighting equipment contain elements like mercury, lead, arsenic, and chromium (Ali et al., 2022). Mercury is also present in paints and can adhere to the steel walls of tankers, contaminating ballast water (Yahya et al., 2012). These elements are associated with cancers of the lungs, liver, kidneys, intestines, and bladder (Hossain et al., 2016). Lead accumulation has toxic effects on the nervous, auditory, and circulatory systems, while mercury primarily targets the nervous system (Rizvi et al., 2020). Studies have reported that levels of Fe, Mn, Cr, As, and Cd in shipbreaking sites often exceed standard limits (Islam et al., 2013).

While ship recycling is economically lucrative and contributes to the sustainable use of global resources, halting such activities is not a viable option. Instead, it is imperative to integrate the concept of a sustainable environment with sustainable economies and development. To achieve this, shipbreaking activities must be conducted in ways that minimize environmental exposure and contamination. Continuous monitoring is essential to promptly address potential contamination (Figure 3). Sustainable practices in ship recycling must prioritize environmental stewardship alongside economic benefits, ensuring a balance between development and ecological preservation.

Figure 3. A snapshot from monitoring activities at a shipbreaking site.

## Pollution Management and Sustainability in Shipbreaking Facilities

In shipbreaking practices, vessels arriving at dismantling yards must come with a "Green Passport." This passport, maintained by the shipowner, should include comprehensive information about the vessel, such as the types of cargo carried during its service life and the materials used in its construction and repairs (Rizvi et al., 2020). (Hossain et al., (2016) have suggested revisiting the shipbreaking industry in an environmentally appropriate manner without ignoring its operational demands and have referred to these dismantling activities under the term "Green Ship Recycling."

Today, many shipbreaking facilities worldwide lack the necessary infrastructure to prevent the release of hazardous waste into the environment. This shortfall is primarily attributed to the economic incapacity of countries where shipbreaking activities are prevalent to establish such infrastructure. Furthermore, the risk of unemployment deters workers from prioritizing health and environmental safety, despite the harsh working conditions that threaten both. This lack of pressure hinders efforts to improve processes.

Rizvi et al., (2020) summarize the deficiencies in shipbreaking yards as follows: there are no laboratories to conduct pre-dismantling testing, nor are there qualified experts to staff them. This situation is largely due to the economic fragility of these countries. Another factor tied to economic limitations is the inadequacy of waste disposal facilities. Many shipbreaking sites lack such facilities entirely. During the transportation of waste to off-site facilities, adherence to necessary standards is also required. However, using non-compliant methods for waste transport poses additional environmental risks. Lastly, contaminations caused by accidents at shipbreaking sites remain a significant risk.

The beaching method, widely practiced in many shipbreaking countries, is unequivocally regarded as the most problematic approach due to its severe environmental and human health impacts. In this method, dismantling begins on mudflats, where all dislodged components and leaks from the ship directly infiltrate the muddy ground, facilitating contamination of both groundwater and the sea. Additionally, particulates released during dismantling disperse into the air and, under suitable atmospheric conditions, eventually settle onto soil, seas, or urban areas, further endangering human and environmental health. Preventative measures against hazardous waste contamination must commence with the planning of shipbreaking operations and be meticulously implemented at every stage.

Rizvi et al., (2020) propose an alternative approach: conducting shipbreaking on specially constructed platforms instead of mudflats. These platforms should be designed with layered materials such as gravel and stone to trap hazardous waste effectively. Establishing and enforcing standards for shipbreaking activities is ultimately the responsibility of governments in these countries.

Lin et al., (2022) highlight the challenges faced by countries like Bangladesh, India, and Pakistan in meeting international standards such as the Hong Kong Convention and the European Union Ship Recycling Regulation. These challenges could potentially constrain raw material supply, economic activity, and employment opportunities. Nevertheless, the authors offer practical recommendations even for countries unable to fully comply with these regulations. They advocate for governments to develop national shipbreaking policies involving all stakeholders, addressing ship imports, working conditions, occupational safety, and the protection of surrounding communities and the environment. Notably, the article emphasizes the importance of degassing ships and cleaning all oil-containing equipment prior to dismantling, with certification of these processes as a crucial measure for safeguarding environmental health.

Hossain et al., (2016) emphasize the importance of a "pre-cleaning process" before cutting ships, aligning with the Technical Guidelines on Environmentally Sound Management (ESM) for the Full and Partial Dismantling of Ships, a document under the Basel Convention. This process involves removing hazardous materials and wastes from the vessel. Among these, flammable wastes can be gasified for reuse as fuel or incinerated using appropriate pollution control methods (Neşer et al., 2008).

The hulls and equipment of ships are known to contain various metals. Given their persistence and potential to bioaccumulate in the food chain, it is crucial to establish methods for removing metals released during shipbreaking activities. Additionally, monitoring air, soil, and water quality around shipbreaking facilities must be carried out with specificity (Jannat et al., 2023).

Several testing methods are available to identify hazardous materials in ships slated for dismantling. One significant challenge is the lack of a globally standardized method for testing asbestos, one of the most hazardous substances (Rizvi et al., 2020). Asbestos removal should occur in controlled, sealed environments equipped with negative pressure systems and filtration mechanisms for air and wastewater. The work should also be performed under humid conditions to minimize risks. For asbestos and metal-containing waste, combining the waste with cement and packaging it in synthetic bags is recommended (Chang et al., 2010).

A key aspect of environmentally sound shipbreaking is the scientific monitoring of dismantling sites after their establishment. Policymakers, owners, scientists, NGOs, local representatives, and all stakeholders must maintain continuous communication and collaboration (Hossain et al., 2016). Besides addressing environmental issues, worker safety must also be prioritized. Employers should provide personal protective equipment, and emergency preparedness measures—such as fire stations and hospitals—should be implemented to minimize losses and facilitate rapid responses to accidents (Hossain et al., 2016).

Although environmental protection regulations in shipbreaking countries often remain lax, efforts to mitigate the degradation of coastal and marine areas are being tightened globally. At the forefront of these initiatives is the International Maritime Organization (IMO), which integrates sustainability principles into every phase of maritime activity. IMO establishes comprehensive standards that span the ship's lifecycle—from construction and operation to eventual recycling (Chang et al., 2010).

Historically, the ship recycling industry was dominated by European countries and the United States until the 1960s. By the 1970s, growing concerns prompted a shift of this industry to South Asia, and since the 1980s, shipbreaking has been conducted almost exclusively in Asia. The primary drivers of this relocation were the availability of cheap labor and increasingly stringent environmental regulations in developed countries.

The first significant international effort to address the environmental impacts of ship recycling was the Basel Convention. However, it was criticized for its limited scope, addressing hazardous material transport but failing to comprehensively regulate the shipbreaking process (Chang et al., 2010). In response, the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships was adopted in 2009. This convention introduces regulations covering the entire lifecycle of a ship, from design and construction to end-of-life recycling.The Hong Kong Convention met its conditions for entry into force in June 2023 and will take effect on June 26, 2025. One requirement was the ratification by at least 15 contracting states, a threshold that has now been surpassed, with 24 states currently party to the convention. These include key shipbreaking nations such as Bangladesh, India, Pakistan, and Turkey (www.imo.org).

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# CHAPTER IV

# FLOW INDUCED MOTION IN HARNESSING HYDROKINETIC ENERGY

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## Abstract

Flow-Induced Vibrations (FIV), encompassing flutter, vortex-induced vibrations (VIV), and galloping, are critical phenomena in fluid-structure interactions with broad engineering applications. This document emphasizes the role of FIV in hydrokinetic energy systems, particularly focusing on VIV due to its efficiency in low-speed flows and self-synchronizing behavior. VIV-based energy harvesters leverage periodic oscillations of submerged structures to convert kinetic energy into electricity using electromagnetic, piezoelectric, or hydraulic systems. The scalability, adaptability, and low-speed efficiency of these systems make them promising for marine hydrokinetic (MHK) applications. However, challenges such as material durability, environmental impacts, and performance under variable flows necessitate innovative solutions like adaptive designs and bio-inspired structures. The study highlights advancements in multi-body configurations, hybrid energy systems, and smart technologies, underscoring the potential of VIV for sustainable energy generation in diverse aquatic environments.

**Keywords:** Flow-Induced Vibrations (FIV), Vortex-Induced Vibrations (VIV), Hydrokinetic Energy Harvesting, Marine Hydrokinetic (MHK)

## 1. Introduction

Flow-Induced Vibration (FIV) is a critical phenomenon within fluid-structure interaction, arising when fluid flow induces oscillatory motion in structures. Highly associated with both structural vibration and fluid dynamics processes such as vortex shedding, boundary layer separation, and wake formation, FIV represents a characteristic challenge in engineering. This phenomenon is observed in diverse structural applications, including riser pipes, transmission cables, bridges, and skyscrapers, where interactions with fluid flow can result in sustained vibrations (Williamson & Govardhan, 2004). Due to its complex physical underlying and broad applicability, FIV has garnered substantial research interest over the past few decades (Sarpkaya, 2004), with significant focus on understanding its mechanisms and applications.

The oscillatory motion of FIV, induced by the interaction between fluid flow and structures, can lead to both advantageous (Bernitsas et al., 2008) and detrimental outcomes (Kim, & Perkins 2002; Matsumoto et al., 2001; Li et al., 2011; Ehsan & Scanlan, 1990), depending on the application. In the context of energy harnessing, FIV provides significant potential for extracting energy from fluid flow, making it a promising area for hydrokinetic energy systems (Khojasteh et al., 2023). Through the physical underlying, FIV can be categorized into three primary forms: fluttering, vortex-induced vibrations (VIV), and galloping (Francis, & Swain, 2024; Lv et al., 2021). Each category is driven by distinct mechanisms and exhibits unique behavioral characteristics when subjected to fluid flow. After briefly exploring these categories, this chapter specifically focuses on VIV for energy applications.

Fluttering is a self-excited oscillation arising from unstable dynamic loads of flow coupling with a structure’s natural frequencies. This phenomenon is associated with dynamic systems with multiple degrees of freedom and involves the interaction of unsteady aerodynamic forces with the elastic deformation of a structure. Flutter is common in streamlined structures like hydrofoils and often observed in aeroelastic structures like bridges, aircraft wings, and turbine blades. Fluttering is driven by continuous energy exchange between aerodynamic forces and the structure's inherent flexibility. In energy systems, fluttering can cause fatigue and damage if not controlled, though certain applications may exploit it under regulated conditions to generate oscillatory motion. Energy generated by fluttering structures can be captured and converted into electricity using either magnetic forces or a piezoelectric material as given in Fig 1.

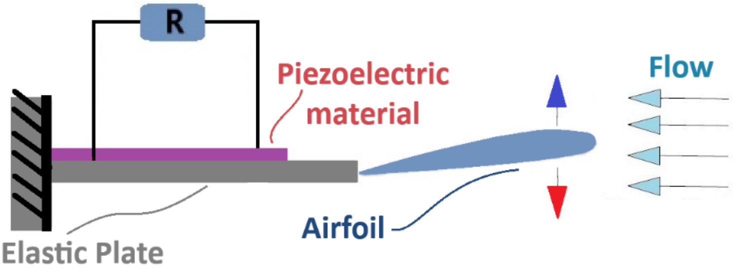

Fig 1. A piezoelectric energy harvester driven by flutter

VIV occurs when alternating pressure fields arise and vortices form on opposite sides of a bluff structure, creating lift forces that act perpendicular to the fluid flow (see Fig 2). As these vortices shed rhythmically, they initiate an oscillating force that synchronizes with the structure’s natural frequency under certain conditions. VIV is especially significant for the structures submerged in water or placed in wind flows, where controlled oscillations can be leveraged to harness kinetic energy. The synchronization between the vortex shedding frequency and the natural frequency of the structure, known as lock-in, enables more efficient energy transfer (Bernitsas et al., 2008). VIV is well-suited for energy extraction as it arises at relatively low flow velocities, making it ideal for hydrokinetic systems designed for rivers, tidal currents, or other low-speed flows (Kim & Bernitsas 2016) even as slow as 0.343 m/s with substantial efficiency (Lv et al., 2021).

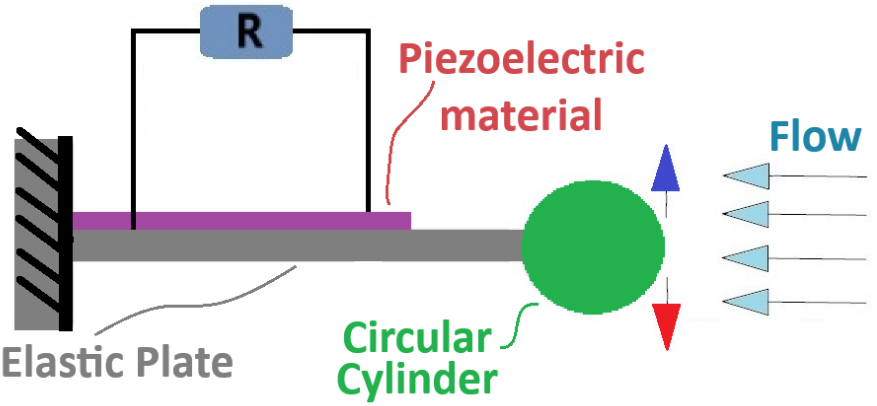

Fig 2. A piezoelectric energy harvester driven by VIV

Galloping is characterized by low-frequency, high-amplitude oscillations commonly found in bluff bodies—structures with non-streamlined shapes. It is typically induced by geometric asymmetry or turbulence, and its amplitude grows with increasing flow velocity unless constrained by structural damping or elastic limits. Unlike VIV, galloping results from asymmetric flow patterns around the body that create unbalanced lift forces. Galloping and flutter are categorized as limit cycle oscillation systems. Galloping is particularly useful in energy harvesting applications due to the larger amplitudes it produces, enabling efficient energy capture from even minor flow interactions as explained by Duranay et al. (2022) in detail. Non-circular shapes, such as rectangular or triangular cross-sections (see Fig 3), are especially prone to galloping, adding design flexibility for energy-extracting structures.

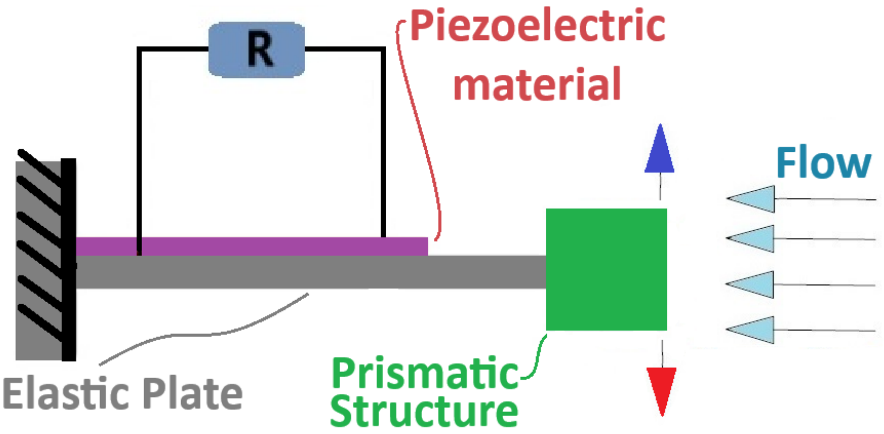

Fig 3. Schematic of a galloping-based piezoelectric energy harvester (Updated from Abdelkefi (2016))

These branches of FIV have found applications in marine hydrokinetic (MHK) energy harnessing, where the goal is to convert the kinetic energy of moving water into mechanical or electrical energy. The Vortex-Induced Vibration Aquatic Clean Energy (VIVACE) converter, as a well-known VIV based example, exemplifies the use of the phenomenon for energy harvesting (Bernitsas et al., 2008), employing alternating lift forces to generate oscillations in cylindrical bodies. This technology effectively harnesses energy even from low-speed flows, overcoming the limitations of traditional steady-lift turbines. Steady-lift turbines are devices that generate power by utilizing the lift forces produced by a steady fluid flow, such as wind or water currents. Unlike conventional drag-based turbines, they rely on aerodynamic or hydrodynamic lift to rotate their blades efficiently. This design can allow for higher energy conversion efficiency and smoother operation in certain steady flow conditions.

Among the briefly explained three types of the phenomena that have unique contributions to energy harnessing, this chapter will primarily focus on VIV. The subsequent sections will delve into the physical background of VIV, its dynamic characteristics, and its role in energy conversion. VIV’s scalability, self-limiting behavior, and efficiency in low-speed flows make it a compelling mechanism for MHK energy applications.

Finally, the final discussion will provide insights into the future potential of FIV-based energy solutions and summarize the benefits and challenges of using these oscillatory behaviors for sustainable energy applications.

## 2. Physical Background of Vortex-Induced Vibrations

VIV is a self-limiting phenomenon that is a subset of flow-induced vibrations, fundamentally driven by the synchronization, or "lock-in," of the vortex shedding frequency with the natural frequency of the structure, resulting in large-amplitude oscillations (Liu & D'Angelo, 2014).

### 2.1 Mechanics of VIV

The dynamics of VIV can be categorized into distinct regimes based on nondimensionalized flow velocity. Nondimensionalized velocity, often referred to as the 'reduced velocity', is a dimensionless parameter used in flow-induced motion phenomena, particularly in the context of VIV. It normalizes the flow velocity relative to the natural frequency of the oscillating body and its characteristic diameter. The reduced velocity is a key factor in predicting and analyzing the response of structures immersed in fluid flows. The relationship between the reduced velocity and the oscillation amplitude is revealed in Fig 4.

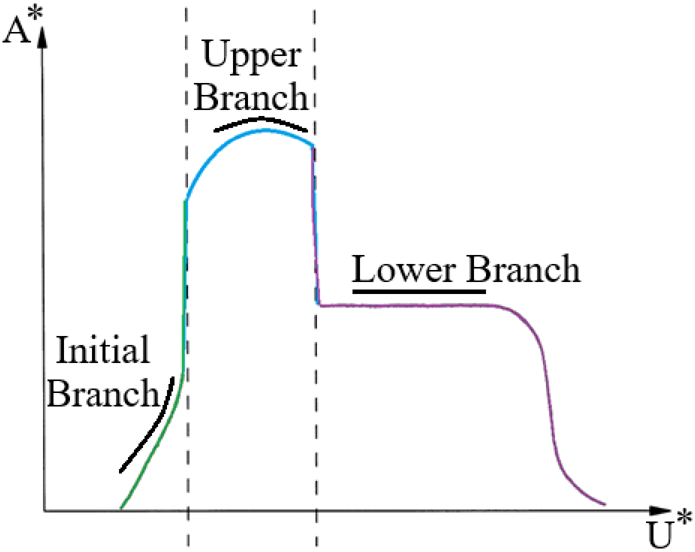

Fig 4. Branches of VIV in Water

The nondimensionalized velocity is mathematically expressed as given in Equation 1:

$$U^* = \frac{U}{f_n D} \tag{1}$$

Where $U^*$ is nondimensionalized (or reduced) velocity, $U$ is flow velocity (m/s) (e.g., velocity of water or air relative to the structure), $f_n$ natural frequency of the structure (typically in still water or air) (Hz), and $D$ denotes characteristic diameter of a structure (m).

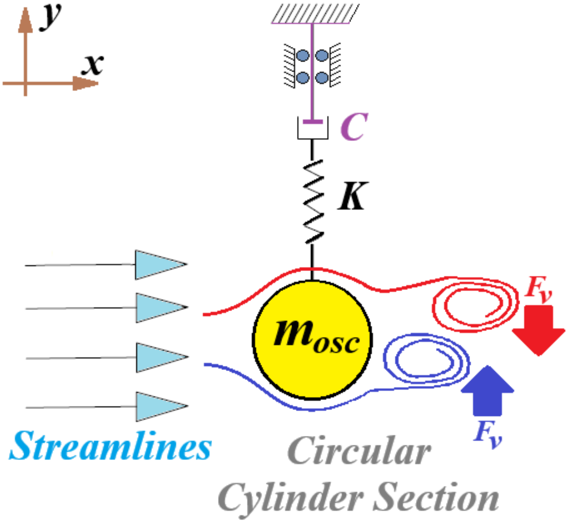

Fig 5. VIV around an elastically mounted circular cylinder

The natural frequency of a structure submerged in water is influenced by both its material properties and the added mass effect ($m_a$) of the surrounding fluid. This is different from the natural frequency in air (or vacuum), as the surrounding water increases the effective mass of the system.

The natural frequency in water, $f_{n,w}$, is calculated as given in Equation 2:

$$f_{n,w} = \frac{1}{2\pi}\sqrt{\frac{K}{m_{osc}+m_a}} \qquad (2)$$

Where $K$ is stiffness of the structure (e.g., spring stiffness) (N/m), $m_{osc}$ is total mass of the oscillating parts (kg), $m_a$ is added mass due to the surrounding water (kg), which accounts for the inertia of the displaced fluid as the structure oscillates. For a smooth circular cylinder in still water, $m_a = m_d c_a$ where $c_a$ is added mass coefficient and equal to 1, and $m_d$ is mass of displaced fluid (kg).

Among the nondimensionalized parameters, reduced velocity and the corresponding Reynolds number may take the key role to determine the conditions under which the vortex shedding frequency aligns with the natural frequency of the structure. Initially, as the flow increases, the oscillations synchronize with vortex shedding, marking the "initial branch". As the system reaches nondimensionalized oscillatory amplitude values above a certain limit ($A^*$≥0.6), it enters "upper branch", characterized by strong resonance and efficient energy transfer between the flow and the structure. At even higher velocities, synchronization weakens, leading to a gradual reduction in amplitude—this transition defines the "lower branch". Eventually, desynchronization occurs, where vortex shedding and structural oscillations fall out of phase, resulting in diminished and irregular vibrations. These transitions are influenced by various factors, including flow conditions and structural properties, making VIV a highly nonlinear and complex phenomenon.

The oscillation amplitude of the oscillating structure is also given in nondimensionalized form where $A^*$ represents the oscillation amplitude normalized by a characteristic diameter of the oscillating body as given in Equation 3:

$$A^* = \frac{A}{D} \qquad (3)$$

Where $A^*$ is also called “reduced amplitude”, $A$ is oscillation amplitude (m), and $D$ denotes characteristic diameter of a structure (m). This nondimensionalization allows for the comparison of VIV responses across different scales and systems by removing the dependence on the structures diameter in the desired direction.

### 2.2 Key Parameters Influencing VIV

Several parameters govern the behavior of VIV and its effectiveness for energy harnessing.

**Reynolds number ($Re$)**, a measure of the relative importance of inertial and viscous forces in the flow, dictates the nature of vortex shedding and the oscillation regimes.

**Strouhal number ($St$)**, which relates vortex shedding frequency to flow velocity and body dimensions, provides a critical scaling relationship for predicting the frequency of oscillations.

**Mass ratio ($m^*$)**, defined as the ratio of the oscillating structure's mass to the mass of the displaced fluid ($m^* = m_{osc}/m_d$), significantly affects the amplitude of vibrations, with lower ratios generally resulting in larger oscillations.

**Structural damping ($\zeta$)** also plays a vital role, as it controls the oscillation amplitude and ensures mechanical stability during energy conversion.

**Phase angle ($\theta$)** refers to the angular difference between the displacement of a vibrating structure and the lift forces generated by vortex shedding. Its role in VIV dynamics is analogous to the function of valve timing in a diesel engine's working principle (Basaran & Ozsoysal, 2017).

### 2.3 Energy Extraction Mechanism

In the context of energy harnessing, VIV presents unique advantages due to its ability to self-synchronize and maintain consistent oscillations over a range of flow velocities. This capability is especially useful in marine hydrokinetic energy systems, where water currents often exhibit variability, compared to turbines or other MHK systems. The process involves coupling the oscillatory motion of the bluff body to an energy conversion system, such as a generator or piezoelectric device. Effective energy extraction requires tuning the natural frequency of the structure to align with the dominant vortex shedding frequency, ensuring optimal lock-in and maximizing energy yield.

To further enhance energy harvesting, recent innovations have focused on introducing adjustable stiffness elements that extend the lock-in range (Sun et al., 2015; Modir & Goudarzi, 2019), enabling efficient operation across wider flow conditions. Additionally, multi-body configurations, where several oscillators are arranged in tandem or staggered arrays (Congpuong et al., 2024), leverage wake interactions to amplify the collective response and increase overall energy output. These advancements highlight the versatility of VIV as a mechanism for sustainable energy harnessing and underscore its potential for widespread application in renewable energy technologies (Li et al., 2024).

## 3. Energy Harnessing with VIV

VIV has emerged as a promising mechanism for energy harnessing, particularly in MHK applications. The periodic oscillations of a structure caused by VIV provide a consistent source of mechanical energy that can also be converted into electrical energy using suitable technologies. This approach is especially advantageous in environments with slow or variable fluid flows, where traditional turbines struggle to operate inefficiently (Lv et al., 2021).

### 3.1 Mechanism of Energy Conversion

In a VIV energy harvester, the oscillations of a bluff body, such as a circular cylinder, are coupled to an energy conversion system. The structure's periodic motion, induced by alternating lift forces from vortex shedding, is transformed into electrical or mechanical energy through one of the following methods:

**Electromagnetic Induction:** The oscillating body moves within a magnetic field, generating electrical current via Faraday’s law as schematically shown in Fig 6.

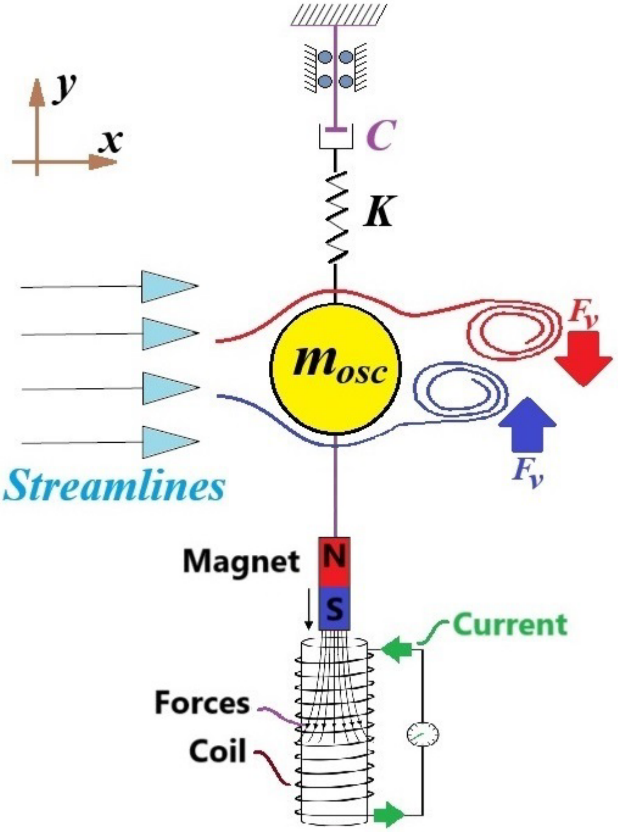

Fig 6. Generating electrical current via Faraday’s law by harnessing a simple VIV mechanism

**Piezoelectric Materials:** Vibrations deform piezoelectric elements, converting mechanical strain into an electric charge as schematically shown in Fig 7.

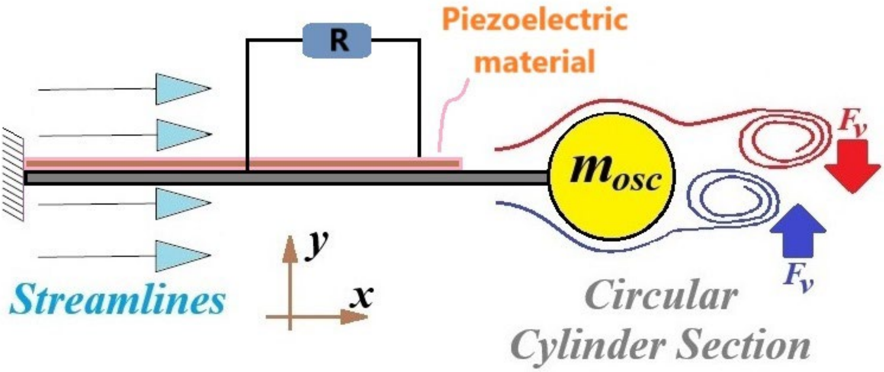

Fig 7. VIV of a circular cylinder deform a piezoelectric element

**Hydraulic Systems:** Oscillatory motion is used to drive a piston, pressurizing a hydraulic fluid to pump water as schematically shown in Fig 8.

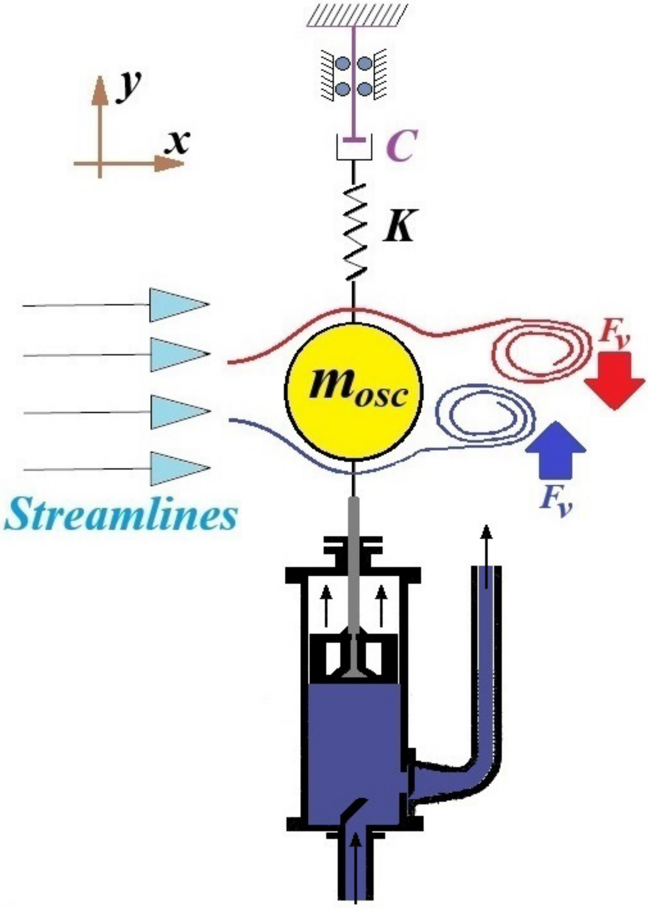

Fig 8. VIV of a circular cylinder drives a lift and force pump

These methods rely on the lock-in phenomenon, where the vortex shedding frequency aligns with the structure's natural frequency, maximizing energy output.

The power that the systems described above will achieve as a result of lift forces driven by VIV can be expressed using Equation 4, similar to that of the VIVACE system used in electricity generation (Bernitsas et al., 2008):

$$P_{harnessed} = \frac{1}{2}\pi C_y A_{cylinder} f_{cylinder} \rho D U^2 L \sin(\theta) \tag{4}$$

Here $P_{harnessed}$ is the power harnessed by VIV of circular cylinder, $C_y$ is lift coefficient acting on the cylinder, $A_{cylinder}$ is amplitude of the cylinder, $f_{cylinder}$ is the frequency of the oscillation, $\rho$ is the density of the ambient fluid, $D$ is the diameter of the circular cylinder, $U$ is the velocity of streaming flow, $L$ is the length of the circular cylinder and $\theta$ denotes the phase angle between the oscillation and the vortex shedding (Duranay, 2024).

### 3.2 Advantages of VIV-Based Energy Systems

VIV-based energy harvesters offer several advantages over conventional technologies:

Low Flow Velocity Operation: Unlike steady-lift turbines, which require high flow speeds, VIV systems can operate efficiently at flow velocities as low as 0.343 m/s in practice (Kim & Bernitsas, 2016; Lv et al., 2021).

Simplicity and Scalability: VIV harvesters typically have fewer moving parts and are easier to scale for different energy demands.

Broad Application Range: These systems can be deployed in rivers, tidal streams, and ocean currents, making them versatile for various MHK applications.

### 3.3 Design and Implementation

Successful VIV energy harvesters require careful design to maximize energy extraction:

Optimizing Structural Properties: Adjusting the mass, stiffness, and damping of the structure ensures that its natural frequency matches the expected vortex shedding frequency in typical flow conditions.

Adjustable Stiffness and Damping: Incorporating nonlinear elements extends the lock-in range, allowing the system to adapt to varying flow velocities (Sun et al., 2015).

Multi-Body Configurations: Arranging multiple cylinders or bluff bodies in tandem or staggered arrays enhances energy output by leveraging wake interactions and increasing oscillatory amplitudes.

### 3.4 Practical Applications

One of the most notable applications of VIV technology is the VIVACE system, developed to harness energy from slow-moving water currents (Bernitsas et al., 2008). By enhancing VIV with passive turbulence control and optimized structural properties, the VIVACE system demonstrates high efficiency even in low-speed flows. Other implementations include piezoelectric harvesters and hybrid devices combining VIV with galloping for broader operational flexibility.

### 3.5 Challenges and Future Directions

Despite its significant potential, VIV energy harvesting faces several technical and environmental challenges. Material durability is a primary concern, as structures exposed to fluid flow undergo continuous oscillations that can lead to fatigue and failure over time. This is particularly critical in marine environments, where materials must also resist corrosion and biofouling. Innovative materials and protective coatings are being explored to enhance the lifespan and reliability of these systems.

Another key challenge lies in optimizing performance under variable flow conditions. Natural water currents, such as those in rivers, oceans, and tidal streams, often exhibit fluctuating velocities and turbulence levels. Designing systems capable of maintaining high energy conversion efficiency across a wide range of operating conditions requires advanced modeling techniques and the integration of adaptive mechanisms. For instance, employing smart materials or adjustable structural components can help systems dynamically adapt to changing flow velocities and maintain synchronization near the lock-in range.

Environmental considerations also pose challenges to the widespread deployment of VIV-based systems. While these systems are inherently more environmentally friendly than traditional energy sources, the potential impact on aquatic ecosystems needs to be thoroughly assessed. The introduction of structures into flowing water can affect sediment transport, local flow patterns, and the behavior of aquatic life. Future research should focus on developing environmentally sensitive designs, such as bio-inspired shapes that minimize ecological disruption while maximizing energy extraction.

To address these challenges, ongoing research is advancing several future-oriented solutions:

- Improving energy conversion efficiency: This includes the use of nonlinear oscillators, multi-body configurations, and advanced damping systems that enhance power output.
- Developing hybrid systems: Combining VIV with other FIV phenomena, such as galloping or flutter, can expand the operational range and increase energy yield in varying flow environments.
- Integrating advanced technologies: Machine learning (ML) techniques can be used for real-time monitoring and optimization of VIV systems, ensuring stable performance and facilitating predictive maintenance.
- Scaling up deployment: Expanding VIV technology to larger arrays or integrating it into existing renewable energy grids requires careful planning and innovative infrastructure designs to ensure compatibility and efficiency.

## 4. Final Discussion

Vortex-induced vibration energy harvesting represents a transformative approach to sustainable energy generation, particularly in marine and other hydrokinetic environments where slow and steady flows are abundant. By harnessing oscillatory motion induced by natural fluid flows, VIV-based systems offer a unique solution to the challenges posed by low-flow velocity regions that are unsuitable for traditional turbines.

This book chapter has explored the physical background of VIV, its mechanics, and its potential for energy harvesting. It also highlighted the advantages of VIV systems, such as their scalability, adaptability, and suitability for low-velocity flows. While challenges remain, including material durability, environmental impact, and variable flow performance, ongoing research is driving significant advancements. By addressing these obstacles, VIV technology could play a crucial role in meeting global renewable energy goals, reducing dependence on fossil fuels, and supporting the transition to a more sustainable energy future.

With continued innovation and interdisciplinary collaboration, VIV energy harvesters could become a cornerstone of renewable energy portfolios worldwide, contributing to the resilience and diversity of energy systems. Their ability to coexist with traditional and emerging technologies further underscores their potential for long-term impact. As research and deployment progress, the next decade could witness a significant leap in the viability and adoption of VIV technology, unlocking its full potential for powering a sustainable future.

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# CHAPTER V

# AUTONOMOUS MARITIME VEHICLES AND THE PROCESS OF AUTONOMY IN THE DEFENSE INDUSTRY

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## Abstract

Autonomous maritime vehicles, with advancements in technology, are undergoing a significant evolution in the maritime and defense industries. These vehicles can be defined as systems that can perform certain tasks without human intervention and can operate autonomously. In the defense sector, the use of autonomous maritime vehicles holds great potential, particularly in critical areas such as submarine defense, surveillance, intelligence gathering, and logistical support. These vehicles have the potential to bring about profound changes in military strategies. Autonomous maritime vehicles have the capacity to carry out operational tasks more safely, at a lower cost, and with higher efficiency. In recent years, the use of autonomous maritime vehicles in the defense industry has gained significant momentum, and the integration of autonomous technologies has made it possible to carry out more comprehensive and diverse operational tasks. These developments have led to the increasing adoption and growing importance of autonomous maritime vehicle technologies in the defense industry. The design of autonomous maritime vehicles typically involves elements such as artificial intelligence, advanced sensor technologies, autonomous navigation systems, and cybersecurity. These technologies allow the vehicle to perceive its environment, navigate using mapping data, and successfully complete specific missions. This study, which examines the potential of autonomous maritime vehicles in future naval defense, aims to assess the importance and impact of this subject in depth. The development of autonomous maritime vehicles in the defense industry is a process that requires a high level of confidentiality and security. Information in this field is often limited due to the sensitive nature of both the technology and the strategic considerations. These vehicles, designed for military purposes, are developed in a few countries, and these developments are generally disclosed to the public in a limited manner to avoid compromising national security. The critical nature and confidentiality of autonomous systems are shaped by factors such as national security concerns, the goal of gaining strategic superiority, and competition in the defense industry. However, one of the biggest challenges in this field is the security, ethical, and legal issues that arise due to the rapid development of technology. The use of autonomous systems on the battlefield can be a subject of debate in terms of international maritime law and military ethics. The future use of these technologies in the military has the potential to significantly transform the strategic structure of naval forces.

**Keywords:** Autonomous Maritime Vehicles, Defense Industry, Artificial Intelligence and Sensor Technologies, Military Strategy and Ethics

## Introduction

Autonomous maritime vehicles (AMV) have gained significant attention in recent years, particularly in fields such as maritime transportation and defense industries. With the help of artificial intelligence (AI), machine learning, advanced sensors, and navigation systems, these vehicles can perform a wide range of tasks without human intervention. In the defense sector, AMVs are used in critical operations like reconnaissance, surveillance, mine clearance, logistics, and even armed attacks. These vehicles help keep soldiers out of harm's way while also increasing operational efficiency and reducing the risks of entering hostile territories by providing high levels of security. However, since technology is still in its developmental stages, challenges related to cybersecurity, ethics, and international law (Cho et al., 2022; Tabish & Chaur-Luh, 2024). The widespread use of AMVs in the future will depend on addressing these issues.

Developed nations are rapidly adopting this technology to enhance the effectiveness of military maritime operations, minimize casualties, and ensure maritime security. This is creating a revolution in the defense industry. Systems like Autonomous Surface Vehicles (ASVs) and Autonomous Underwater Vehicles (AUVs) are being employed for a wide range of missions, including reconnaissance, surveillance, mine clearance, logistical support, and attack operations. Compared to manned vehicles, AMVs can complete tasks more quickly and efficiently while offering operational advantages at lower costs (Kurt & Aymelek, 2022, 2024). Furthermore, these vehicles use high-precision sensors and AI-based algorithms to collect real-time data, which can enable rapid strategic decision-making in combat situations.

On a global scale, major powers such as the United States, China, and the European Union are leading the way in this field, while developing countries are adopting this technology to strengthen their maritime defense capabilities. As AMVs become more prevalent in military applications, they are becoming an integral part of these nations' defense strategies. However, for this technology to be effectively deployed on a global scale, the technical, ethical, and legal challenges must be overcome.

The Turkish defense industry is also undergoing significant development in the field of AMVs (Türkiye Yüzyılı, 2021). Similarly, Türkiye aims to use these vehicles for critical tasks such as maritime security, mine clearance, reconnaissance, and surveillance. Through local and national production, Türkiye is strengthening its independence in this area, enhancing the capabilities of its naval forces, and aiming to project a stronger presence in strategic maritime zones. These advancements not only bolster Türkiye's defense capacity at sea but also contribute to sustainable progress in national security and the defense industry.

In this chapter, it is aimed to explore the potential use of AMVs in the defense industry and the development process of this technology. This study will assess the innovations brought by autonomy to the defense industry in terms of operational efficiency, security, and cost advantages, while also addressing the technical, ethical, and legal challenges associated with the technology. Additionally, it will examine Türkiye's efforts in domestic production in this field and its goals of establishing a stronger presence in strategic maritime zones, aiming to investigate the role of AMVs in national security and the defense industry.

This chapter is structured as follows: First, the evolution of AMVs in the defense industry and their development process will be discussed. Then, key technologies such as artificial intelligence, sensors, machine learning, and navigation systems enabling these vehicles will be examined. The section on applications of AMVs in the defense industry will explore their use in tasks like reconnaissance, surveillance, mine clearance, logistics, and attacks. Next, the chapter will address the cybersecurity, ethical, and legal challenges that hinder their widespread use. Türkiye’s domestic production efforts section will highlight Türkiye’s advancements and strategic goals in this field. Finally, the future of these vehicles in defense and their impact on national security will be explored. This chapter aims to provide a comprehensive analysis of AMVs' role in defense and Türkiye’s strategic objectives in this area.

## The Autonomy Process of Maritime Vehicles in the Defense Industry

The process of autonomizing maritime vessels in the defense industry has undergone a significant transformation in recent years, driven by rapid technological advancements (Gu et al., 2021). Traditional maritime vessels are operated by human crews, while AMVs are emerging as highly independent systems capable of performing tasks without human intervention, thanks to the integration of complex software and hardware systems (Brushane, 2021; Namazi & Perera, 2024). This shift has been made possible following the successful use of autonomous systems in unmanned aerial vehicles (UAVs) and ground vehicles, leading to a similar revolution in maritime systems (Brinkmann et al., 2017). Naval vehicles were initially remotely controlled, but over time, the integration of sensors, AI, machine learning, and advanced navigation systems led to the development of autonomous systems (Council, 2005; Kim et al., 1996; Kobyliński, 2018; Reis et al., 2021; Singh, 2016).

AMVs were first used in military applications for simpler tasks like reconnaissance and surveillance (Veal et al., 2019). However, with technological progress, these vehicles began to perform more complex operations. They are now effectively utilized in critical military missions such as anti-submarine warfare, mine clearance, logistics support, and attack operations (Pastore & Djapic, 2010; Zhao et al., 2019). The development of autonomous systems has accelerated with the ability of these vehicles to respond to environmental factors, high-precision sensors, and AI-based decision-making processes. These vehicles have great potential to minimize the risks that may occur in manned operations and to ensure operational continuity. For example, in anti-submarine warfare, AMVs can use high-precision sensors to detect and track enemy submarines. Similarly, in minesweeping and patrol missions, unmanned systems can perform critical tasks without risking human life. AMVs also offer tactical advantages such as maneuverability and the ability to evade enemy radar systems through features such as low radar signature.

The process of automation is not only a technological innovation but also has profound effects on international defense policies and strategies. AMVs play a critical role in military operations, including logistics, reconnaissance, and targeting, while also holding strategic significance in areas such as protecting maritime borders and acting as a deterrent against illegal activities at sea (Coito, 2021). However, the use of autonomous systems raises ethical and legal questions. In particular, how autonomous vehicles, capable of making decisions without putting human lives at risk, will be monitored in accordance with international laws of war and humanitarian values is becoming one of the most important areas of debate that will shape the future development of these technologies (Morrow, 2018; Tanasescu, 2018).

The process of autonomizing maritime vessels is creating a major transformation in the defense industry, offering many advantages, from operational efficiency to safety. However, for these technologies to be used effectively, both technical infrastructure and legal frameworks must be robustly developed. It is essential to remember that while autonomous systems can be used to gain strategic superiority, especially in naval forces, ethical and legal oversight must not be overlooked.

## Fundamental Technologies of Autonomous Maritime Vehicles

The core technologies of AMVs are shaped by the combination of multiple disciplines, and the success of these systems largely depends on advanced sensor technologies, AI, data processing algorithms, and communication systems (Öztürk et al., 2022; Pokorny et al., 2021; Thombre et al., 2020). First and foremost, the sensors used to enable AMVs to perceive their environment are of crucial importance. These sensors allow the vehicles to perform critical functions such as navigation, environmental analysis, and situational awareness. Technologies such as Light Detection and Ranging (LiDAR), radar, sonar, cameras, and thermal imaging systems are among the key technologies that enable AMVs to collect and analyze environmental data (Clunie et al., 2021). In particular, sonar technology plays a critical role in underwater detection, while LiDAR and radar systems are used for detecting obstacles on the surface. The integration of these sensors ensures that the vehicle can operate safely and efficiently.

AI and machine learning algorithms play a central role in the decision-making processes of AMVs (Walker et al., 2022). These algorithms process environmental data to determine routes, avoid obstacles, and perform various tasks. Deep learning and advanced data processing methods are among the primary software that enhance the decision-making capabilities of maritime vehicles, making them more independent. For example, AMVs can analyze sonar and radar data to identify the type of targets and develop strategic movements accordingly (Ferri et al., 2018). Additionally, autonomous systems continuously undergo learning processes based on environmental data to increase their level of autonomy, which allows the system to function more accurately and efficiently over time.

Advanced communication systems are another crucial technology that supports the operational capabilities of AMVs (Martelli et al., 2021). These vehicles can work in a coordinated manner by exchanging data with a central command unit or other autonomous vehicles (Coker et al., 2013). To enable communication over long distances, wireless systems using satellite communication, radio frequency (RF), and internet connections are commonly employed. These systems provide critical infrastructure, particularly for maritime vehicles that operate at high speeds and engage in prolonged missions. Additionally, for autonomous systems to communicate securely and without interruption, they must be resistant to jamming attacks. Therefore, the use of encrypted and secure communication protocols is of paramount importance for ensuring the operational safety of AMVs.

Finally, the navigation and mapping technologies of AMVs form a fundamental building block for their ability to operate independently (Choi et al., 2020; Stutters et al., 2008). Global Navigation Satellite Systems (GNSS) and inertial navigation systems (INS) are used to verify the vehicle's location and accurately follow its route. However, in situations where GPS signals are weak or lost, such as underwater, the vehicles must rely on sensor data to maintain internal navigation. This requires advanced algorithms and sensor integrations for the vehicle to achieve full autonomy. The ability of AMVs to accurately perceive and navigate such complex environments will provide a significant strategic advantage in the long term for both naval forces and the commercial sector.

## Usage Purposes of Autonomous Maritime Vehicles in the Defense Industry

AMVs are capable of effectively performing surveillance and reconnaissance missions on the surface, underwater, and in the air (Bauk, 2020; Murphy et al., 2008). These vehicles, particularly utilized by border security, naval forces, and coast guard units, can scan large maritime areas to detect potential threats and monitor specific regions (Klein, 2021; Savitz et al., 2020). With high-precision sensors and AI-based analytics, autonomous vehicles are equipped to track both surface activities and underwater movements.

AMVs also play a critical role in mine detection and neutralization operations (Dobref et al., 2023). Without putting human personnel at risk, these vehicles can carry out mine clearance missions, ensuring the safety of maritime traffic and clearing sea lanes. This application is vital for enhancing maritime security, especially in conflict zones and along strategic sea routes.

Furthermore, AMVs can be used to detect, track, and neutralize enemy submarines (Johnson, 2002). Equipped with advanced sonar systems and other sensors, these vehicles can identify submarines and contribute effectively to anti-submarine warfare (ASW) operations. Some versions of AMVs can even be equipped with torpedoes, thus becoming a direct threat to submarines.

In certain cases, AMVs can carry unmanned aerial vehicles or drones on the surface of the water (Krystosik-Gromadzińska, 2021). This enables the creation of an integrated surveillance and reconnaissance network across both maritime and aerial domains, significantly enhancing operational coverage. Drones can monitor surface activity while simultaneously conducting aerial surveillance, providing continuous and dynamic monitoring across a broader area.

AMVs can also be integrated into warships, enhancing their surveillance and reconnaissance capabilities (Agarwala, 2022). These vehicles can be used for specific tasks, such as monitoring the area around the ship. By continuously observing the ship's surroundings, autonomous vehicles can undertake various missions, improving the operational efficiency of the warship while keeping the crew out of harm’s way.

In conclusion, AMVs offer significant advantages in terms of security, efficiency, and cost-effectiveness within the defense industry. As they become an integral part of naval warfare strategies, these vehicles will contribute to the enhancement of operational capabilities, the safety of personnel, and the overall effectiveness of military operations.

## Technical, Ethical and Legal Challenges

One of the biggest challenges to the widespread use of AMVs in the defense industry is the serious cybersecurity risks they face (Cho et al., 2022). AMVs rely on highly digitized and interconnected systems, which makes them vulnerable to cyberattacks (Symes et al., 2024). Particularly, as these vehicles operate through remote command and control systems, cyber threats could manipulate their navigation systems, communication infrastructure, or sensor data (Cheung, 2022). An adversarial state or malicious actor could disrupt the vehicle's functionality, potentially hindering military operations or damaging strategic targets (Tabish & Chaur-Luh, 2024). This presents significant risks, especially in military operations, as security vulnerabilities could lead to the failure of critical defense systems. In this context, AMVs require continuously updated and resilient encryption systems, strong authentication methods, and threat detection algorithms to ensure their security. However, current technologies may not be fully equipped to counter these threats, creating a major security gap.

Ethical issues are another significant factor that hinders the use of AMVs in defense (Johansson, 2018). Particularly in military operations, the absence of human oversight in the decision-making processes of autonomous systems raises major ethical concerns. Autonomous vehicles, especially when it comes to target identification and attack decisions, raise serious questions regarding compliance with the laws of war and international humanitarian law. The decision-making capability of an AMV over a manned ship or civilian targets is directly related to the ethical norms embedded in its design. Additionally, the potential for errors in these systems' decision-making processes could result in consequences that put human lives at risk. Since autonomous systems must be designed and monitored in a way that avoids violations of human rights during wartime, the use of these vehicles must be closely monitored by military leaders and the international community (Krishnan, 2016; Thorne, 2020). The ethical responsibilities of autonomous vehicles and the oversight of operations carried out by these vehicles are not only technological but have also become a societal issue.

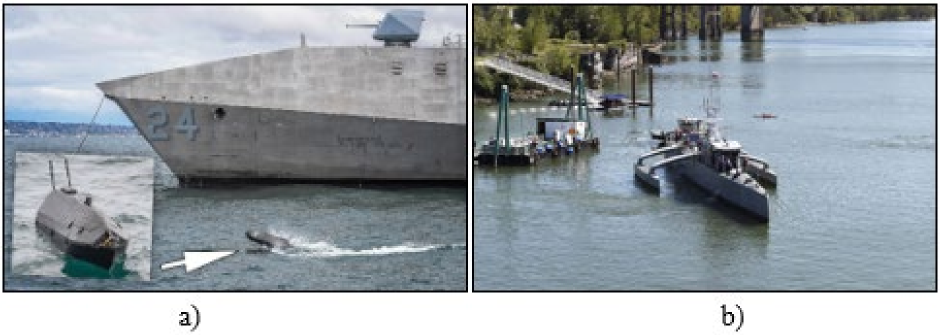
International law presents another significant barrier to the widespread use of AMVs in the defense industry(Chang et al., 2020; Klein, 2019; Klein et al., 2020). Current maritime regulations are primarily based on manned vessels, and there are significant gaps regarding how autonomous systems can be integrated into this framework. International regulations, such as the United Nations Convention on the Law of the Sea (UNCLOS), address issues like sovereignty rights, boundary definitions, and rules governing naval warfare, but they do not provide a clear framework for how AMVs will comply with these regulations (Coello, 2023). During military operations, AMVs could potentially violate another state’s sovereignty or create uncertainties regarding accountability in incidents occurring in international waters. The use of autonomous systems also raises challenges related to compliance with international humanitarian law during warfare. For example, an attack carried out by an AMV might raise questions about whether the targeted area is civilian or whether the attack was proportionate. In this context, there is a need to establish a new international regulatory framework for autonomous systems and to define clear rules regarding accountability for these systems' actions.

For AMVs to be used effectively and safely in the defense industry, strong security measures, ethical standards, and international legal frameworks must be established. While the potential of autonomous systems in defense is substantial, realizing this potential is a complex process that requires overcoming the challenges outlined above. Improvements in both technological and legal domains will ensure that these vehicles can be used effectively within secure, ethical, and legal frameworks.

## Domestic Production Efforts in the Field of Autonomous Maritime Vehicles

Many countries are working on AMVs in the defense industry, with the United States, China, the United Kingdom, Israel, and Türkiye standing out as the most important. Due to reasons such as being a continental power, having a large portion of its military deployed far from the mainland, and having coastlines along the oceans, these countries have configured autonomous technologies for use in logistics vessels.

The United States, one of the world's largest maritime industries, has numerous projects in AMVs. Among the test-phase projects, which are typically small in size (ranging from 1 to 2 meters), notable ones include "Adaro", while larger projects like the "Seahunter", measuring 40 meters, have gained significant attention as leading examples of overseas AMVs (Newdick, 2021; Turner, 2018).



a) Adaro - *Image: Office of Naval Research*
b) Sea Hunter - *Image: U.S. Navy/Lt. Nicholas Ransom*

**Figure 1 – Autonomous Maritime Vehicles of the United States**

To be effective in the Persian Gulf and maintain its presence, the U.S. is implementing numerous mini AMV projects (America's Navy, 2023). In addition to 8-meter-long autonomous vehicles for ensuring the security of the Oman Sea, Strait of Hormuz, and Bab el-Mandeb Strait, there are also mini autonomous vehicles, about 2 meters in length, that will be used for tasks such as intelligence gathering and monitoring maritime traffic, while also providing protection against piracy and safeguarding commercial vessels (Mosly, 2023).

The United States is focusing on enhancing its logistics capabilities through Large Unmanned Surface Vehicles (LUSV). The Spearhead Class Expeditionary Transfer Dock Ships are designed to rapidly deliver battalion-sized military forces and critical cargo to nearly any location worldwide under all conditions (Manuel, 2024). These ships are capable of supporting military operations as well as providing logistical assistance during natural disasters. For instance, the USNS Apalachicola can operate for up to 30 days without human intervention (Austal, 2023). The Ranger Class Expeditionary Transfer Dock Ships are part of the U.S. strategy to increase logistical capacity, with testing activities currently accelerated (Baird Maritime, 2022). In September 2021, the Ranger Unmanned Surface Vehicle (USV) successfully launched a Standard Missile-6 from its Mk 41 Vertical Launch System, showcasing its advanced capabilities (Eckstein, 2022). Additionally, the Ranger-class vessel carries a customized Aegis Weapon System package, further demonstrating its potential for versatile and effective missions.

a) USNS Apalachicola - *Image: Austal*
b) Ranger - *Image: US Navy/Mass Communication Specialist 1st Class Tyler Fraser*

**Figure 2 – Unmanned Surface Vehicles of the United States**

China has shown a serious interest in AMV to strengthen its maritime security and naval forces. The country is focused on developing a variety of maritime vehicles, including submarines, surface ships, and AMVs. China has short-range USV projects aimed at enhancing its presence in the geopolitically and commercially critical South China Sea, where it seeks to monitor commercial activities. Due to the vast distance from the U.S. mainland, larger and displacement-based vessels are required, which significantly influences the design of the USV being produced.

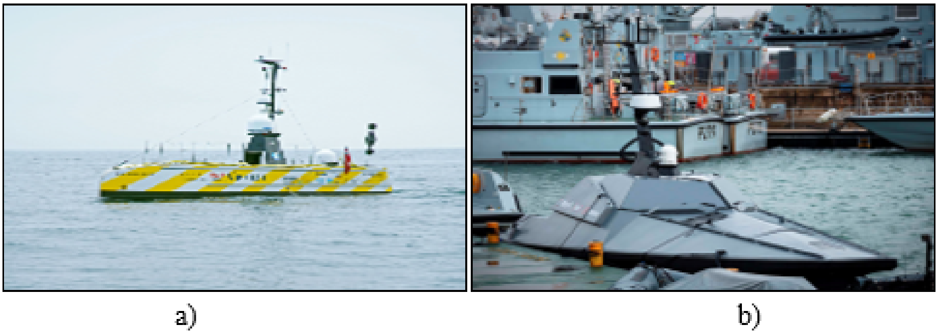
In 2019, China introduced the JARI-USV, an unmanned surface vehicle approximately 15 meters long with a displacement of 20 tons (Army Recognition, 2019). The JARI-USV is equipped with advanced capabilities such as phased-array radar systems, vertical launch systems, and torpedoes, enabling it to perform air defense, anti-ship, and anti-submarine missions. The vessel is armed with a 30mm gun mounted on the foredeck and a laser-guided rocket compartment. Additionally, it features a four-cell Vertical Launch System (VLS) and central positions for surface-to-air missiles (SAM) and 324mm torpedo tubes, making it a highly versatile and strategic asset for China in the region.

a) JARI-USV - *Image: www.hisutton.com*
b) JARI-USV-A - *Image: www.hisutton.com*

**Figure 3 – Unmanned Surface Vehicles of China**

The JARI-USV-A, a larger variant of the 20-ton JARI-USV, offers insight into China's rapid progress in autonomous maritime systems (Gencer, 2024). The ship's modular systems enhance its versatility by allowing for various payload configurations, making it adaptable to a wide range of missions. This development of the USV indicates China's focus on creating a larger, potentially more versatile platform. Despite this, it aligns with China's broader goals of expanding its unmanned maritime vehicle capabilities, mirroring the U.S. Navy's "Sea Hunter" concept, which aims to enhance autonomous capabilities in naval operations (Sutton, 2024).

The UK Ministry of Defence, in collaboration with Sonardyne, which has established a significant presence in underwater robotics technology, is developing navigation systems for autonomous surface vehicles (Lee, 2022). The Sea-Kit X class of USV, which is 12 meters long, is currently being tested with sensors typically used in underwater USVs(Geo Matching, 2024). The Madfox USV, designed for high-speed operations with a 13-meter hull, is capable of remote-controlled usage (Royal Navy, 2021a). During its trials, the Madfox demonstrated the ability to perform certain tasks autonomously, supported by the MAPLE autonomous command and control system (Royal Navy, 2021b). The Madfox is particularly well-suited for supporting and protecting warships, as it also incorporates secure communication technologies to enhance its operational safety.



a) Sea-Kit X - *Image: www.sea-kit.com*
b) Madfox - *Image: LPhot Bradley*

**Figure 4 – Unmanned Surface Vehicles of the United Kingdom**

Israel's AMVs are widely exported to various countries worldwide, playing a crucial role in strengthening the nation's naval defense and contributing to regional maritime security. Among the key systems developed by Israel are the IAI Blue Whale, and the Elbit Systems Seagull. The IAI Blue Whale, a 12-meter long mini-submarine, is designed for detecting submarines and gathering acoustic intelligence(IAI, 2023, 2024). The Elbit Systems Seagull, also measuring 12 meters in length, is a USV capable of performing a variety of tasks, including mine countermeasures, anti-submarine warfare, as well as intelligence and reconnaissance missions (Elbit Systems, 2024). These advanced systems highlight Israel's significant contributions to the field of autonomous naval technologies.

a) IAI Blue Whale - *Image: Israel Aerospace Industries*
b) Elbit Systems Seagull - *Image: www.elbitsystems.com*

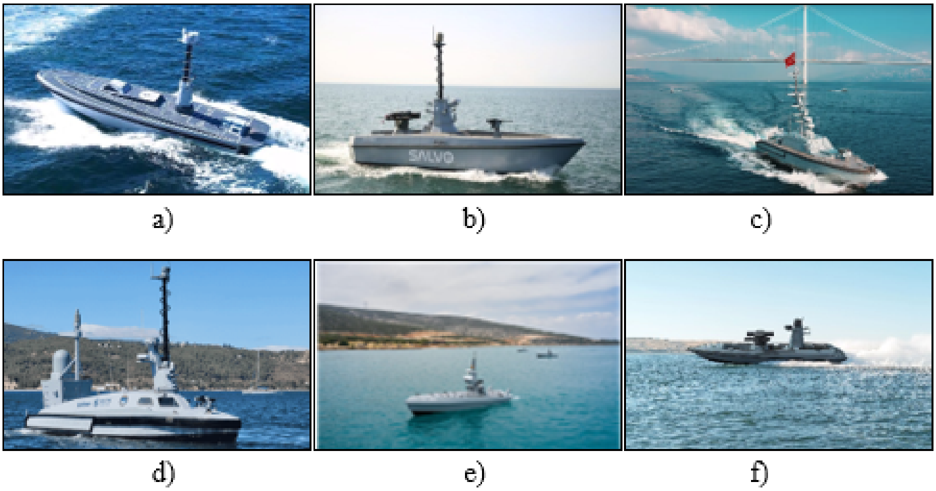
**Figure 5 – Unmanned Maritime Vehicles of Israel**

In Türkiye, significant efforts are being made in the defense industry regarding autonomous/unmanned maritime vehicle technologies, with a particular focus on meeting the needs of the Turkish Navy. When examining USVs produced in Türkiye, various models such as Ulaq, Salvo, Marlin, Albatros, Mir, and Sancar can be seen (Türkiye Yüzyılı, 2021). These USVs are typically designed to protect Türkiye's interests in the Aegean Sea, Mediterranean, and Black Sea. The operational flexibility provided by their ability to be deployed in allied, coastal countries is an added advantage. These vehicles can be transported by cargo planes or trucks and launched into the sea via cranes. Additionally, they can be launched and recovered from the Turkish Navy’s multipurpose amphibious assault ship, TCG Anadolu (Sunnetci, 2022).

Sancar allows for a more cost-effective execution of various missions by carrying different payloads with its modular design. Sancar is approximately 13 meters in length, with a maximum speed of 40 knots. It has a minimum range of 400 nautical miles and can operate in 4 sea states.

Salvo enables cost-effective mission execution by carrying various payloads thanks to its modular structure. Salvo is approximately 15 meters in length and can reach speeds of 45-60 knots. It has a minimum range of 400 nautical miles and can operate in 4 sea states.

Mir is capable of speeds up to 40 knots and a range exceeding 600 nautical miles. It can operate for nearly 4 days without requiring refueling, and it is highly maneuverable and capable of performing missions even in challenging sea conditions.



a) Sancar - *Image: Turkish Defence Industry Agency*
b) Salvo - *Image: Dearsan Shipyard*
c) Mir - *Image: Turkish Defence Industry Agency*
d) Marlin - *Image: Aselsan*
e) Albatros-S - *Image: Aselsan*
f) Ulaq - *Image: Ares Shipyard*

**Figure 6 – Unmanned Surface Vehicles of Türkiye**

Marlin allows for cost-effective execution of various tasks by carrying different payloads with its modular design. Marlin is approximately 15 meters long, has a maximum speed of 36 knots, and a minimum range of 400 nautical miles. It can operate in 4 sea states. Marlin is the first USV in the world to have electronic warfare capabilities and to participate in a NATO exercise.

Albatros-S is a USV swarm system with high level autonomy capability, capable of navigating and performing tasks in a swarm formation independent of a central control, and capable of carrying different payloads.

Ulaq allows for the cost-effective execution of various missions by carrying different payloads with its modular design. Ulaq is approximately 12 meters in length, can reach a maximum speed of 35 knots, and has a minimum range of 210 nautical miles. It can operate in 4 sea states.

The primary objective of these unmanned maritime vehicles is to ensure maritime security by patrolling Türkiye's continental shelf and exclusive economic zones, particularly in the Aegean, Mediterranean, and Black Seas. These USVs are also equipped with mine detection and neutralization capabilities, which can be employed in the Black Sea to address the mine-related challenges that have emerged following the Russia-Ukraine conflict. These vehicles play a crucial role in defending Türkiye's national interests at sea, enhancing maritime security, and providing effective response capabilities in crisis situations. Operating in strategic regions such as the Aegean, Mediterranean, and Black Seas, the USVs contribute significantly to Türkiye’s maritime security and defense strategies, reflecting the country’s determination to safeguard its sovereignty.

## Conclusion and Future Perspective

AMVs are emerging as a revolutionary technology in the defense industry. These vehicles stand out for their ability to perform military operations autonomously and without human intervention. While traditional vessels face the physical and psychological limitations of their crew, autonomous systems overcome these obstacles, enabling efficient operation in long-term and continuous missions. Additionally, these vehicles have the potential to minimize human error and, when used in critical tasks such as detecting, tracking, and neutralizing enemy units, can provide strategic advantages. These advancements could lead to fundamental changes in naval warfare doctrines.

From a national security perspective, the integration of AMVs offers significant contributions to enhancing maritime security and protecting borders. These vehicles will enable states to better control their maritime domains by performing tasks such as reconnaissance, intelligence gathering, and threat analysis. Furthermore, the low production and maintenance costs of autonomous vehicles can have a positive impact on defense budgets. With their flexible and rapid response capabilities, these vehicles can provide operational superiority in the implementation of national security strategies. However, the integration of autonomous systems also brings cybersecurity risks, necessitating careful monitoring of technological developments in this area.

In terms of their impact on naval forces, AMVs have the potential to reduce personnel casualties while making naval operations more sophisticated. These vehicles offer significant advantages in terms of operational flexibility and speed in both territorial waters and international waters. The integration of AMVs could lead to the development of new tactics and strategies, potentially reshaping naval interactions. However, the widespread adoption of this technology will require the development of new regulations and norms, both in military and international law. Ultimately, AMVs will not only enable naval forces to conduct more effective and secure operations on the battlefield but also become a key element of future military strategies.

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# CHAPTER VI

# BASIC PRINCIPLES OF NEWBUILD SHIPYARD FACILITY LAYOUT PLANNING AND SOLUTION APPROACHES TO PROBLEMS

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## Abstract

Shipyard facility layout planning is a critical aspect of ensuring efficient production processes in shipbuilding. This study examines the fundamental principles of newbuild shipyard facility layout planning and the problem-solving approaches used in the literature. Effective layout planning reduces production costs, improves workflow, and optimizes material handling, while also addressing challenges such as limited space, complex workflows, and the potential for future expansion. The shipyard layout process is broken down into three stages: preliminary design, basic design, and detailed design, each requiring increasing levels of complexity and customization. Key factors influencing shipyard layout include flow, space, activity relationships, and safety considerations. This paper also reviews various methodologies employed in the literature for shipyard layout design, including simulation-based frameworks, hybrid algorithms, and optimization models. Additionally, two example shipyard layouts from previous studies are presented to illustrate practical applications of these methodologies. These layouts focus on minimizing material handling costs, improving production efficiency, and ensuring seamless integration of support activities into the production process. The findings highlight the importance of strategic planning in achieving operational efficiency, reducing logistical delays, and enhancing shipyard competitiveness. Future research should continue to refine these methods, incorporating advanced optimization techniques to meet the evolving demands of the shipbuilding industry.

**Keywords:** Shipbuilding, newbuild shipyard, facility layout planning

## Introduction

Facility layout design is the process of planning the optimal layout of physical facilities to increase resource utilisation in production activities. Ensuring an efficient production flow is important to minimise production costs and maximise efficiency by reducing the labour spent on the production line (Deshpande et al., 2016; Scalia et al., 2019). The layout of workstations is also one of the important factors for production efficiency in shipbuilding. In addition, shipyard layout planning is the first step to be taken in the construction of a shipyard (Lee et al., 2014), but it is a very complex and difficult process. Shipyard facility layout planning is generally carried out to optimise material flow, ensure safe working conditions and speed up production processes. This process is therefore of critical importance as it also helps to reduce production costs. An appropriate facility layout planning will increase the competitive power of the shipyard.

The shipyard facility layout planning process presents challenges such as limited space utilisation and the organisation of complex workflows. In addition, creating a flexible design to meet possible future expansion needs is a critical factor for the long-term success of shipyard planning. Another important challenge is to make appropriate arrangements for the type of production, as shipyards may carry out different activities, such as both newbuilding and maintenance and repair work. On the other hand, shipyards usually carry out project-type production, meaning that each ship has its own unique design and requirements. This increases the complexity and makes it difficult to establish a standardised production line. However, in some shipyards, although limited, a process close to mass production can be realised by focusing on specific ship designs. The differences between these two production types affect many aspects, from the organisation of workstations to the movement of materials and equipment. In project-type production, specific workflows and space requirements are planned for each project, whereas in mass production, more fixed and optimised processes are applied. Shipyard facility layout planning should take into account the various challenges and different requirements for production types, but with the right planning and flexibility, these challenges can be overcome, and a more efficient ship production process can be achieved.

## An Overview of Shipyard Layout Principles

In general terms, the facility is defined as the production departments including equipment, machinery and employees where production is carried out. The facility layout problem is the study of determining the most appropriate layout of these departments that make up the entire production area (Akça & Şahin, 2018). Shipyard facility layout planning process can be handled in three stages (Song & Woo, 2013): The first stage is a preliminary design process in which the locations of the main work areas within the shipyard are determined. The second stage is the basic design process in which a conceptual design is developed by considering more detailed production data than the first stage and this conceptual design is iteratively updated and improved. The third stage is the detailed design where each production site is analysed in detail. In this last step, details such as the activities, size and internal layout of the facilities are also finalised. In shipyard facility layout planning, the process becomes more complex as it goes from preliminary design to detailed design. While the basic layout design determines the overall structure, detailed design requires taking into account the individual characteristics of all facilities. This stage requires an in-depth examination of the specific requirements of each workstation and the development of customised solutions. Therefore, detailed design stands out as an area that is difficult to cover completely in a single study due to its scope and level of detail (Kafali, 2025).

It can be stated that there is a hierarchical activity structure in the shipbuilding process. In other words, there are main activities and sub-activities connected to them. Therefore, it is necessary to know the main and sub-activities performed in the shipyard for shipyard facility layout planning. Thus, a shipyard facility layout that will ensure efficient organisation of the workflow and effective use of resources in the shipbuilding process can be provided. At the top level of the activity hierarchy, design, procurement, planning, steel construction, piping, outfitting, painting, erection on the slipway, in water assembly, testing and delivery can be specified. Each of these main activities includes different sub-activities. Considering the layout of the shipyard, the largest area is occupied by steel construction production activities. Outfitting, piping, and painting facilities follow. As the ship blocks are progressively produced in the steel construction area, material flows from both the piping and outfitting facilities towards the blocks. Therefore, if the mentioned facilities are far and disconnected from each other, it will disrupt the flow.

## Key Factors Considered in Shipyard Facility Planning

Many factors affect the layout of a facility. Product characteristics, production technology, occupational safety requirements, work ergonomics, costs, in-plant logistics and similar factors are among these considerations. These elements show that facility layout planning is a multidimensional problem. This makes layout planning an inherently complex and challenging process (Kudelska, 2018). Shipbuilding involves the production of large and complex structures, which are often designed and built to the specific requirements of the customer (Shin et al., 2009). This character of the shipbuilding industry requires a customised production process planning in line with product diversity. In this context, the factors taken into account when designing the shipyard facility layout are determined in a way to meet this diversity and flexibility requirement. According to the literature review, the factors considered for the shipyard facility layout plan are given in Table 1.

Table 1. Factors considered in shipyard facility layout planning based on literature review.

| **Reference** | **Factors** |
|---|---|
| Song & Woo (2013) | Flow, relation, and cost |
| Shin et al. (2009) | Flow, activity, and space |
| Matulja et al. (2009) | Flow, activity, and space |
| Choi et al. (2017) | Flow, shape of the workstation, space, adjacency, and alignment |
| Türk et al. (2021) | Flow, geometry, adjacency |
| Tamer et al. (2022) | Flow, activity relationships, geometry, and adjacency |
| Junior et al. (2023) | Flow, geometry, adjacency, and alignment |
| Kafalı (2025) | Flow, activity, and risk |

If the factors given in Table 1 are examined, in shipyard facility layout planning, flow plays a critical role in ensuring that production processes proceed smoothly, continuously, and efficiently. Flow encompasses the movement of materials, equipment, and workers, and when well-designed, it positively impacts many aspects of the production process. Properly planned flow minimizes unnecessary movements of materials and processes, reducing time losses and increasing efficiency. Additionally, optimizing flow plays a significant role in reducing production costs. It decreases material handling times and logistical expenses while enhancing the efficient use of energy and resources. Furthermore, it enables the effective utilization of the facility's space, with workstations and storage areas arranged accordingly. Since different production processes in shipbuilding are interconnected, designing a harmonious flow facilitates integration between these processes.

**Relation** is another key factor that directly influences the efficiency and harmony of production processes in shipyard facility layout planning. The connections between workstations, storage areas, internal logistics routes, and other facility components must be carefully examined and effectively planned. Failing to establish these relationships properly can result in inefficiencies, wasted time, and increased costs. Shipbuilding involves highly interconnected and complex production stages. For example, the distances and transport routes between workstations, from block fabrication to outfitting and final assembly, significantly impact production timelines and workloads. Proper planning of these relationships ensures smoother workflows and optimized use of resources. Moreover, relations in shipyard layout are not limited to physical placements; they also involve fostering operational synergy and coordination among different processes. This makes relation planning a strategic element for achieving long-term efficiency in shipyard operations.

**The activity factor is crucial in shipbuilding facility layout planning because it serves as the foundation for the manufacturing process.** Identifying the main and sub-activities accurately ensures the effective planning of the spaces, equipment, and workforce needed to carry out these activities. Since activities define the operational flow of a shipyard, they are the cornerstone of facility layout planning. The diversity and complexity of activities in shipbuilding require each stage to be addressed in detail. For instance, activities such as material preparation, mounting, full welding, grinding, block production, outfitting, surface treatments, and final testing each have specific space and equipment requirements. Ensuring harmony between these activities is essential for maintaining an uninterrupted production flow. Moreover, a detailed analysis of activities is necessary to enhance the efficiency of current processes and to create a flexible layout plan for future operations. Proper activity planning improves material flow between workstations, reduces transportation times, and lowers production costs. Therefore, effectively defining and sequencing activities in shipyard layout planning is vital not only for short-term operational success but also for achieving long-term strategic goals.

Cost is an important consideration when developing the layout of shipbuilding facilities to ensure effective and sustainable operations. Optimizing the layout of the shipyard in terms of cost affects not only the initial construction expenses but also operational costs, maintenance expenses, and long-term return on investment. A well-designed layout ensures the efficient use of resources, reducing material handling, labour, and equipment costs, which ultimately lowers production expenses. The cost factor is directly related to the efficient organization of space within the shipyard. Proper placement of workstations, storage areas, and production lines prevents unnecessary movements and time loss. Poor layout planning, on the other hand, can lead to high transportation and logistics costs during operations. Therefore, placing each facility component in harmony with one another optimizes both transport and labour costs. Furthermore, factors such as energy consumption, equipment efficiency, and maintenance costs should also be considered in layout planning. Optimizing energy use and ensuring the efficient operation of equipment can result in significant long-term cost savings. For this reason, cost is an important consideration in shipbuilding facility layout development, both for short-term financial gain and for long-term viability.

Proper use of space in shipyard layout allows for the efficient placement of workstations, storage areas, material handling routes, and other facility components. Efficient space management reduces unnecessary movement and time loss, helping to maintain a smooth and continuous production flow. Shipbuilding is a complex process that requires large areas and resource-intensive operations. Each production stage has specific space requirements. For example, activities like mounting, welding, block production, painting, outfitting, etc. may require vast and specialized areas. Insufficient or poorly allocated space can create barriers between these activities, disrupt workflow, and extend production timelines. Proper space planning is also essential to the shipyard's long-term effectiveness. Not only can space optimization improve the efficiency of existing procedures, but it also offers flexibility to meet future demands for development and expansion. Space is therefore crucial for increasing production efficiency, cutting costs, and ensuring operational flexibility when designing the architecture of shipyards.

The shape of the workstation directly affects the movement of labour, materials, and equipment in shipbuilding. A well-designed workstation optimizes work processes and minimizes unnecessary movements, preventing time loss. This is a key factor in improving production efficiency. In shipyards, each workstation is customized to meet the specific requirements of a production process. Therefore, the shape of the workstation should be determined based on the type of activities carried out at that station. For example, different design shapes are required for activities such as cutting, preproduction, curved panel production, block production, grinding-painting, outfitting, or testing. The shape of the workstation should be ergonomic, allowing work to be completed more quickly and efficiently. Additionally, the layout of the workstation should facilitate easy movement of materials and ensure that tasks are carried out in the correct sequence. Furthermore, the shape of the workstation also impacts the overall flow of the production line. A well-designed workstation layout helps regulate the movement of materials and labour, ensuring smoother and uninterrupted production processes. A good design reduces material handling times, prevents unnecessary transport, and lowers production costs.

Placing workstations, storage areas, and other facility components that are directly connected or frequently interact close to each other (known as adjacency) accelerates the production process and reduces costs. In shipbuilding, processes typically progress in an integrated manner. For instance, a block assembly station should be located near the cutting and pre-fabrication stations, as material transfers occur continuously. Similarly, outfitting and painting facilities should be positioned in alignment with final assembly processes. Such strategic layouts shorten transportation distances, prevent time loss, optimize energy and resource usage, and reduce production costs. Furthermore, adjacency enables production processes to flow more smoothly. It reduces coordination issues between workers and equipment, minimizing operational errors and delays. Proper adjacency planning enhances not only workflow efficiency but also the overall ergonomics and safety of the facility.

In shipyard facility layout planning, alignment plays a critical role in enhancing production efficiency and reducing costs. Proper alignment of production lines and workstations ensures a seamless flow of operations, which is particularly effective in minimizing material handling costs (Choi et al., 2017). Aligned sections allow materials to move directly from one workstation to another, avoiding unnecessary movements along the production line. Furthermore, alignment enables more efficient resource sharing. For instance, departments positioned along the same production line can utilize equipment, labour, and logistical resources more effectively. This contributes to speeding up overall production processes and reducing expenses. Given the complexity and integrated nature of shipyard operations, alignment serves as a strategic element in organizing workflows and improving overall facility efficiency.

The geometry factor encompasses more than just the physical shape and arrangement of workstations in the shipyard. It also includes the physical characteristics of intermediate products produced at these stations, the requirements of the processes, and the movement paths throughout the facility. Therefore, geometry extends beyond the shape of workstations to become a critical factor in designing layouts that align with all dimensions of production processes. For example, consider the production of ship blocks. These are large, complex, and heavy structures whose shapes, dimensions, and transportability directly influence the geometric arrangement of workstations. If a ship block needs to be transported from the block production area to the final erection site (i.e. slipway or dock), the transportation paths and their connections to workstations must be designed in harmony with the block's dimensions. While the shape of workstations is an integral part of geometric planning, it should also correspond to the size of the products being produced, the transport routes, and the nature of the processes. Further influencing geometric considerations are the production procedures carried out at workstations. For instance, the workspace required for cutting, panel lines, and painting must be designed to suit the geometric requirements of each process. Geometry also has a direct impact on the movement of materials and equipment. Effective geometric planning ensures that materials are transported along the shortest and least energy-intensive paths. This reduces logistical costs while optimizing the use of labour and equipment. For example, unnecessary turns, narrow passageways, or insufficient space during transportation slow down production speed and increase the likelihood of operational errors.

The risk (safety) component is crucial when designing the layout of shipbuilding facilities. Shipyards are places with complex production processes that involve heavy equipment, large ship blocks, and hazardous materials. Therefore, properly assessing risks plays a critical role in ensuring the safety of workers while also guaranteeing the efficiency and continuity of production processes. Considering risk factors ensures that workstations and facility components are designed in accordance with safety priorities. For example, the layout of hazardous areas, fire exits, and emergency plans must be positioned correctly. Additionally, organizing the distances between workstations, material transport routes, and worker movements is crucial to minimize risks. Proper safety planning helps prevent workplace accidents and enhances the health and safety of employees. Furthermore, safety also contributes to improving employee well-being and fostering a safety culture within the organization. This, in turn, boosts production efficiency and operational success, while reducing operational costs. Proper management of risk factors leads to a safety-focused approach in shipyard facility layout planning, creating a more efficient, safer, and sustainable working environment in the long term.

## Shipyard Layout Planning Methodologies and Approaches in The Literature

The facility layout planning of newbuild shipyards holds strategic importance for enhancing the efficiency of production processes, reducing costs, and ensuring a safe working environment. This planning process is shaped by specific fundamental principles due to the complexity and interconnected nature of shipyard operations while also requiring the development of innovative approaches to address encountered challenges. Research on the facility layout planning of shipyards is limited, with only a restricted number of studies available in this field.

Shin et al. (2009) suggested a system engineering-based shipyard layout design framework. A simulation-based layout design is also included in this framework. Matulja et al. (2009) present a four-phased methodology for generating a shipyard preliminary layout. They establish and examine different production layout configurations. Analytical hierarchy process and systematic layout planning approaches are used in the study.  Song & Woo (2013) present a method for layout design that includes real product data from the target ship as well as actual shipbuilding process data. They employed a hybrid heuristic algorithm for the preliminary layout design. Choi et al. (2017) utilize material handling costs as a basis for generating shipyard layouts. They suggest a two-stage approach that incorporates topological and geometrical optimizations. The research applies both genetic algorithms and stochastic growth algorithms. Dixit et al. (2020) propose a two-stage approach using the fuzzy similarity index and the fuzzy goal programming model. The initial stage involves practitioners creating alternative layouts and relationship charts. These charts use subjective assessments of factors like process flow, material flow, distance, and cost. The fit of each layout to the ideal is then evaluated. However, implementing the ideal layout may face feasibility issues due to practical constraints. Hence, a fuzzy goal programming model is formulated in the second stage, considering these constraints. Türk et al. (2021) research the best topological configuration for a shipyard by reducing the expense of material handling. In addition to applying the quadratic assignment problem model, they also determine the most suitable genetic algorithm approach and operator group. Tamer et al. (2022) look into the issue of a medium-sized shipyard's facility layout. The systematic layout planning and graph-theoretical approach methodologies are used to develop a number of shipyard layouts, and these alternatives are then evaluated using the efficiency rate method. Junior et al. (2023) discuss the optimization of shipyard facility layout to minimize material handling costs. The authors propose a sequential structure of algorithms for topology optimization and geometry optimization to optimize the layout of shipyard facilities. In addition, the paper emphasizes the importance of well-defined closeness conditions in shipyard layout to ensure uninterrupted production flow and lower manufacturing costs. In Kafali's study (2025), a hierarchical methodology for shipyard preliminary layout was developed. The study addresses the factors of risk, activity, and flow, with the weights of these factors determined through the analytical hierarchy process and expert opinions. Subsequently, proximity ratings were calculated using fuzzy logic, and in the final stage, alternative preliminary shipyard layouts were generated using the simulated annealing optimization algorithm.

## Example Shipyard Layout Plans

In studies conducted on shipyard layout, various methods and strategies have been developed by considering factors such as activity relations, material flow, safety, and efficiency. The complex production processes and dynamic structures of shipyards have led to a diversification of research in this field and the development of tailored solutions for each facility. In this part of the study, two example shipyard layouts suggested in previous studies are provided.

The shipyard layout seen in Figure 1 reflects a structure designed to facilitate production processes and optimize material flow. The positioning of initial workstations, such as the steel stockyard (a) and steel shop (b), is notable for aligning with the initial stages of the production process. These areas are located to ensure easy access to materials. Subsequent production stages, including the paint shop (c) and sub-assembly area (d), are positioned close to the panel fabrication area (e) and block erection area (f). This arrangement reduces material transport distances, contributing to time and cost savings in logistical processes. The dock (g) and quay (h) are strategically placed at the final stage of the production line, where the final block assembly and ship launching occur. This layout supports a linear and fluid structure for the production line, enabling seamless transitions between processes. Additionally, the grouping of support stations such as the pipe shop (k), outfitting shop (p), and general-purpose shop (o) in a designated area ensures the efficient integration of auxiliary activities into the production process. Facilities aimed at worker welfare, such as the medical centre (i) and canteen (j), are positioned in accessible locations.

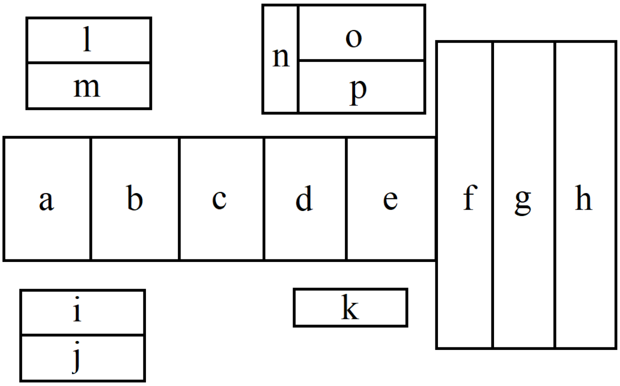

Figure 1. An example shipyard layout (Dixit et al., 2020)

Table 2. Names of the workstations seen in Figure 1.

| | | | |
|---|---|---|---|
| a | Steel Stockyard | i | Medical Centre |
| b | Steel Shop | j | Canteen |
| c | Paint Shop | k | Pipe Shop |
| d | Sub-Assembly Area | l | Design Office |
| e | Panel Fabrication Area | m | Supporting Activities |
| f | Block Erection Area | n | Warehouse |
| g | Dock | o | General Purpose Shop |
| h | Quay | p | Outfitting Shop |

In the alternative shipyard layout seen in Figure 2, it is evident that the workstations are arranged in a logical sequence to ensure the fluidity of production processes. Stations related to the initial stages, such as the stockyard (a), profile cutting area (b), and CNC cutting area (c), are positioned close to each other to ensure that the first steps of production are completed quickly and efficiently. The preassembly areas (d, e, f) and panel production area (g), which follow immediately after the cutting processes, are integrated into the production line without disrupting material flow. This arrangement minimizes logistical delays and enhances production efficiency. The block production areas (h), which occupy a central and extensive location, form the core of the production line. This central structure facilitates the transport of interim products to the blocks, saving time and labour. The slipway (j) is strategically placed at the final stage, serving the purpose of final assembly and ship launching. Additionally, support stations such as the paint workshop (l), mechanical workshop (m), and piping workshop (o) are evenly distributed around the production line. The placement of the trash and waste material area (u) outside the production zone provides a significant advantage in terms of safety and cleanliness. Overall, this layout emphasizes operational efficiency by organizing production processes in a hierarchical flow and reducing material handling distances.

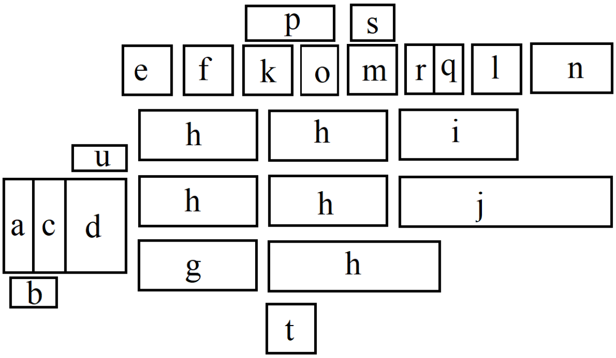

Figure 2. An example shipyard layout (Tamer et al., 2022).

Table 3. Names of the workstations seen in Figure 2.

| | | | |
|---|---|---|---|
| a | Stockyard | l | Paint Workshop |
| b | Profile Cutting Area | m | Mechanical Workshop |
| c | CNC Cutting Area | n | Block Buffer Zone-2 |
| d | Preassembly Area-1 | o | Piping Workshop |
| e | Preassembly Area-2 | p | Piping Warehouse |
| f | Preassembly Area-3 | q | Dining Hall |
| g | Panel Production Area | r | Design Office |
| h | Block Production Area | s | Ventilation and Electricity Shop |
| i | Block Buffer Zone-1 | t | Woodshop |
| j | Slipway | u | Trash and Waste Material Area |
| k | Warehouse-1 | | |

## Conclusions

Shipyard facility layout planning plays a crucial role in ensuring an efficient production process, minimizing costs, and optimizing material flow. The various methodologies and approaches discussed in this study reflect the complexity and challenges involved in designing an optimal shipyard layout. These methods take into account a variety of factors, such as flow, activity, space, geometry, and safety, to create layouts that facilitate smooth production operations. As shipyards often deal with large-scale and intricate production processes, these layouts must be adaptable to future changes and capable of accommodating different types of work.

The two example shipyard layouts presented in this study illustrate different approaches to the placement of workstations and production stages. These examples demonstrate the importance of a well-thought-out shipyard facility layout in achieving operational efficiency, safety, and long-term success. Further research and advancements in scientific techniques, such as the application of fuzzy logic, genetic algorithms, and simulation models, will continue to enhance the effectiveness of shipyard layout planning, ensuring that future shipyards remain competitive and capable of meeting the demands of the ever-evolving maritime industry.

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# CHAPTER VII

# COMPARATIVE ANALYSIS OF ELECTRIC AND FOSSIL FUEL OUTBOARD MOTORS IN COMPOSITE BOATS: A SUSTAINABILITY AND PERFORMANCE PERSPECTIVE

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## Abstract

Composite materials and outboard motors have heralded a transformation in the maritime industry. Replacing traditional materials, composite materials are increasingly preferred in the production of modern boats due to their properties such as lightweight, durability, and corrosion resistance. Additionally, outboard motors, especially electric models, contribute to reducing environmental impacts and enhancing energy efficiency in marine vessels. This chapter aims to examine the technological framework of composite boats and outboard motors. Initially, the properties, advantages, and applications of composite materials in boats are explained. Subsequently, a comparative analysis of outboard motors, particularly electric and conventional models, is conducted to enhance the performance of these vessels.

The use of electric outboard motors has seen a sharp increase in recent years and plays an important role in environmental sustainability. These motors offer advantages such as low noise levels, zero direct emissions, and energy efficiency but face limitations such as battery capacity and costs. In contrast, conventional motors provide high performance and long range but have negative aspects in terms of carbon emissions and maintenance costs. This study provides a detailed comparison of the advantages and disadvantages of different motor types, presented in tabular form.

Finally, this chapter discusses future research areas and points that need improvement from technological and environmental perspectives for sustainable maritime operations. In this context, the importance of advancements in battery technologies for electric outboard motors and the necessity to improve cost-efficiency in composite material production processes are emphasized.

**Keywords:** Outboard motors, electric motors, fossil fuel motor

## 1. **Introduction**

As global emphasis on sustainable practices increases, many industries have begun reassessing traditional methods. The maritime sector, heavily reliant on fossil fuels, has also been affected by this trend. In recent years, the need to develop environmentally friendly technologies in the maritime industry has grown. Global issues such as climate change, marine pollution, and ecosystem degradation are key drivers for technological solutions. In this context, the advantages of composite boats, such as their lightweight nature, durability, and energy efficiency, present an important option for environmental sustainability (Önal & Neşer, 2018). The use of new motor technologies in composite boats to minimize environmental impacts and improve energy efficiency is also gaining importance (Vásquez et al., 2024). Electric outboard motors offer advantages such as zero direct emissions, low noise levels, and lower operating costs compared to traditional fossil fuel-powered motors. However, the performance and economic differences between these two types of motors are critical for the industry (Łapko, 2019).

Outboard motors are a widely used propulsion system in many boats. Additionally, electric outboard motors minimize carbon footprint and other environmental impacts by eliminating fossil fuel usage.

This section details the comparison of electric and fossil fuel outboard motors from sustainability, performance, and economic perspectives in composite boats. Known for their lightweight nature and corrosion resistance, composite materials provide an ideal platform for testing these propulsion systems (Rubino et al., 2020).

## 2. Technological Framework of Composite Boats and Outboard Motors

### 2.1. Structure and Properties of Composite Materials

Composite materials combine the properties of two or more different substances to create a new structure. Commonly used composite materials in boats consist of components such as fiberglass, carbon fiber, and epoxy resin (Rubino et al., 2020). These materials offer advantages such as lightweight, high strength, and corrosion resistance (Önal & Neşer, 2018). Composite materials are particularly formed by combining fibers like fiberglass, carbon fiber, and aramid with polymer matrices, and they find extensive applications in marine industries.

These materials are suitable for a wide range of structural components, from ship hulls to propellers. The lightweight nature of composite materials enhances vessel speed while reducing fuel consumption. Additionally, their resistance to corrosion lowers maintenance costs and extends their lifespan (Rubino et al., 2020). In modern shipbuilding, composite materials have revolutionized performance and durability, especially in small boats and racing vessels.

### 2.1.1 Environmental Advantages

Lightweight: Composite materials are lighter than traditional materials such as aluminum and steel. Lightweight boats reduce the energy consumption of the motor, thereby lowering carbon emissions.

Corrosion Resistance: Composite materials, being resistant to seawater and chemical effects, reduce maintenance requirements and provide long service life. Energy-Efficient Production: The production of composite materials requires less energy compared to steel and aluminum manufacturing, resulting in a smaller carbon footprint.

## 2.2 Features of Composite Boats

Composite boats are manufactured using materials such as fiberglass, carbon fiber, and aramid fibers. These materials are known for their lightweight nature, high tensile strength, and resistance to environmental degradation (Önal & Neşer, 2018). Studies on the applications of fiber-reinforced composites in marine industries have highlighted advantages such as weight reduction, increased buoyancy, and reduced maintenance costs (Rubino et al., 2020).

Composite materials have revolutionized the maritime industry with their properties of lightweight, high strength, and corrosion resistance. Thermoset polymer composites, such as glass-reinforced plastics (GRP), have replaced traditional materials like wood and steel in the production of marine vessels. Particularly for smaller boats up to 50 meters in length, composite materials have become the most preferred manufacturing material with a 70% market share (Önal & Neşer, 2018).

These materials offer advantages such as high durability, workability, and cost efficiency. GRP demonstrates superior resistance to UV radiation, seawater, and marine organisms in ocean environments.

## 2.3 Outboard Motor Technology

Outboard motors have long been used as an ideal power source for boats (Reabroy et al., 2015). Initially powered by internal combustion engines, this technology has now entered a new era with the proliferation of electric motors. Traditional motors offer high power and long range, while electric motors provide advantages in terms of low emissions and energy efficiency. However, both systems are suitable for different applications and technical requirements. For instance, electric motors are preferred for water sports and tourist boats due to their quiet operation and eco-friendly features (Porru et al., 2020 - 2020).

Fossil Fuel Motors: Fossil fuel outboard motors, typically internal combustion engines, deliver high power output. However, emissions such as $CO_2$ and $NO_x$ have adverse effects on marine ecosystems (Gaggero et al., 2024).

Despite their environmental disadvantages, fossil fuel motors continue to dominate the market due to their range and power output. Advancements in two-stroke and four-stroke engine technologies have improved their performance. However, emissions from these motors impact water quality (Juttner et al., 1995a).

Electric Motors: Electric motors operate on lithium-ion batteries and produce zero emissions. Additionally, their quiet operation minimizes noise pollution, making them ideal for use in sensitive ecosystems (Reabroy et al., 2015).

Electric propulsion systems have gained popularity due to their high energy efficiency, zero on-site emissions, and quiet operation. The study "Is it Time for Motorboat E-Mobility?" (Łapko, 2019) highlights that electric outboard motors are particularly suitable for urban and recreational applications.

### 2.3.1 Electric Outboard Motors

#### 2.3.1.1 Operating Principle and Efficiency

Electric motors derive power from electric batteries as their energy source and convert mechanical energy directly into motion. This process results in higher efficiency compared to internal combustion engines; while energy efficiency in electric motors can reach up to 90%, it is considerably lower in internal combustion engines (Kaya et al., 2021). Electric motors provide instant torque, making them suitable for precision applications. Performance tests conducted on the electric motors demonstrate consistent speed and range capabilities under varying conditions (Epropulsion, 2019).

#### 2.3.1.2. Environmental Advantages

Carbon Emissions: Electric motors operate on a zero-direct-emission principle. When the energy used is sourced from renewables, the carbon footprint can be minimized. They produce no on-site emissions, and their lifecycle emissions depend on the energy source used for electricity generation. In regions where renewable energy is utilized, their sustainability is enhanced (Vásquez et al., 2024).

Noise Pollution: Electric motors operate at 20-30 dB lower noise levels compared to internal combustion engines, reducing adverse impacts on sensitive marine species (Gaggero et al., 2024).While electric motors run quietly, fossil fuel motors contribute to underwater noise pollution, disrupting aquatic behaviors (Whitfield & Becker, 2014).

Risk of Fuel Spills: The use of electric motors completely eliminates the risk of water pollution caused by fuel spills.

### 2.3.2 Conventional Internal Combustion Engines and Their Environmental Impacts

Internal combustion engines deliver higher peak power outputs but are less efficient. Test drive reports highlight their superiority in long-distance operations. Fossil fuel-powered engines stand out in terms of range due to the high energy density of fuels like gasoline. In contrast, electric systems are limited by battery capacity and are ideal for short trips.

#### 2.3.2.1. Fossil Fuel Consumption

Internal combustion engines run on fossil fuels and produce higher carbon emissions. They release greenhouse gases and pollutants, causing harm to aquatic and atmospheric ecosystems (Juttner et al., 1995b).

#### 2.3.2.2. Noise and Impacts on Marine Ecosystems

These motors generate high noise levels, adversely affecting marine life. This disruption can interfere with communication, navigation, and hunting behaviors.

#### 2.3.2.3. Fuel Spills

Fuel spills and improper storage practices lead to toxic accumulations in marine ecosystems. This is particularly damaging to sensitive ecosystems like coral reefs. Oil and fuel spills from internal combustion engines introduce harmful substances into water bodies, negatively impacting aquatic organisms.

### 2.3.3 Economic Analysis

#### 2.3.3.1 Initial and Operating Costs

Electric Motors: Higher initial costs, but lower operating expenses.
Fossil Fuel Motors: Lower initial costs, but susceptible to fluctuations in fuel prices.

Table 1. Features for Gasoline and Electirc Outboard Motors

| **Features** | **Gasoline Outboard Motor** | **Electric Outboard Motor** |
|---|---|---|
| Power Output | 50 HP | 50 HP |
| Fuel/Energy Type | Gasoline | Electricity (Lithium-ion battery) |
| Emissions | $CO_2$, $NO_x$, HC and paticulate matter | Zero direct emissions |
| Fuel Consumption | Approximately 18.9 litres per hour at full load. | Approximately 37.3 kWh per hour at full load |
| Operating Costs | Depends on gasoline prices. For instance at 1.5 USD/L, approxiamtely 28.35 USD per hour | Depends on electricity prices. For instance, at 0.13 USD/kWh, approximately 4.85 USD per hour |
| Noise Level | 85-100 dB | 50-60 dB |
| Weight | 100 kg (excluding fuel) | Motor: 50-60 kg; Battery: 50-100 kg |
| Maintenance Requirements | Regular oil and filter changes, fuel system maintenance | Low maintenance; battery and electrical system checks |
| Lifespan | 10-15 years (depending on usage and maintenance conditions) | Motor: 15-20 years; Battery: 5-10 years |
| Environmental Impact | High; exhaust emissions and potential fuel spills | Low; zero exhaust emissions and no risk of fuel spills |
| Initial Cost | Lower (~10,000-12,000 USD) | Higher (~15,000-20,000 USD) |
| Charging/Refueling Tİme | Quick; a few minutes | 4-8 hours (depending on charging infrastructure) |
| Application Areas | Long-distance travel, applications requiring high speeds | Short to medium-distance travel; quiet and eco-friendly operations |

## 3. **Advantages of Electric Motors**

The proliferation of electric outboard motors is an important development for environmental sustainability. Traditional two-stroke motors cause environmental issues due to high fuel consumption and emissions, whereas electric motors minimize these impacts. However, the widespread adoption of electric motors requires advancements in battery technology and reductions in costs. Furthermore, the development of energy management systems and charging infrastructure will play a crucial role in accelerating this transition.

Electric motors do not emit harmful gases during operation, contributing to improved air quality and significantly reducing the carbon footprint of vessels. For example, the annual carbon emissions of a 10 kW electric outboard motor can be minimized to the lowest levels when charged with renewable energy.

Electric motors are much quieter than traditional internal combustion engines, which is especially important for marine ecosystems.

Electric motors are up to 90% more efficient in energy conversion processes compared to internal combustion engines. While a higher portion of energy in fossil fuel engines is lost as heat, electric motors convert energy directly into mechanical power.

### 3.1. Composite Boats with Electric Motors

Electric outboard motors used in composite boats offer an environmentally friendly solution. When combined with a lightweight composite hull, these motors further reduce energy consumption. Statistics indicate that a composite boat measuring 20-30 feet in length consumes 50% less energy with electric motors compared to internal combustion engines. Additionally, these boats have the potential to integrate with renewable energy sources, such as solar panels or wind turbines.

## 4. Conventional Internal Combustion Engines

Conventional internal combustion engines rely on fossil fuel usage, resulting in high carbon emissions. On average, a gasoline-powered outboard motor consumes approximately 3000-4000 liters of fuel annually, emitting around 10-12 tons of $CO_2$ in the process. Additionally, harmful emissions such as nitrogen oxides ($NO_x$) and particulate matter are produced during operation.

Internal combustion engines generate high levels of noise, particularly in underwater environments, negatively affecting the communication and navigation abilities of fish and other marine organisms. Fossil fuel-powered motors contribute to environmental pollution due to fuel spills and waste oil. Just one liter of petroleum can contaminate up to one million liters of water.

Fluctuations in fossil fuel prices and the maintenance costs associated with internal combustion engines lead to high long-term operational expenses. Electric motors reduce these costs with their lower maintenance requirements.

## 5. Case Studies

### 5.1. Galápagos Islands

Efforts to transition water taxis to electric propulsion demonstrate economic feasibility and environmental benefits. Local operators prioritize lightweight systems with reliable charging infrastructure (Vásquez et al., 2024).

### 5.2. Recreational Use

Recreational users report high satisfaction with electric motors due to their quiet operation and ease of use. Performance evaluations of ePropulsion systems highlight their practicality for leisure activities (Epropulsion, 2019).

Table2. Electric and Conventional Motors Comparison

| Feature | Electric Motors | Conventinal Motors | Reference |
|---|---|---|---|
| **Environmental Impact** | Provides zero direct emissions, environmentally friendly. | High carbon emissions due to fossil fuel usage. | (Marshall, 1971; Epropulsion, 2019; Łapko, 2019, 2016; Reabroy et al., 2015; Porru et al., 2020 - 2020; Otsuka et al., 2007; Berlin Selva Rex et al., 2023) |
| **Fuel Economy** | Low operating cost, offers low cost per charge. | High fuel cost, dependent on fuel prices. | |
| **Range** | Depends on battery capacity, generally suitable for short distances. | Superior for long distances, dependent on fuel tank capacity. | |
| **Noise Level** | Very low, operates quietly; ideal for water sports and fishing. | Higher, noticeable noise levels during operation. | |
| **Speed and Performance** | Optimal performance at medium speeds; battery depletes quickly during sudden acceleration. | Provides high speed and performance, capable of maintaining steady speeds for long durations. | |
| **Maintenance Requirements** | Low maintenance due to fewer mechanical parts. | Requires regular maintenance (oil changes, filters, etc.). | |
| **Ease of Installation** | Easily integrated into boats due to its lightweight and modular structure. | Heavier and more complex to install. | |
| **Cost** | High initial investment; battery prices are high. | Lower initial investment but higher operating costs. | |
| **Operating Principle** | Converts electrical energy directly into motion, offering high energy efficiency. | Converts fossil fuel into energy, with greater energy losses. | |
| **Application Areas** | Suitable for conservation areas, tourist regions, and water sports. | More suitable for long-distance fishing and commercial applications. | |
| **Sustainability** | Can be charged with renewable energy, low environmental footprint. | Not sustainable due to fossil fuel usage. | |

## 6. Conclusion and Recommendations

Electric motors offer environmental sustainability and economic advantages compared to fossil fuel-powered motors. However, technological limitations and high initial costs present barriers to widespread adoption.

The transition to electric propulsion in composite boats reflects broader sustainability goals. While fossil fuel motors provide unique range and power for specific applications, electric systems are cleaner, quieter, and increasingly viable alternatives. Continuous advancements in battery technology and regulatory support are critical in shaping the future of maritime propulsion systems.

Renewable Energy Infrastructure: Encourage the use of solar panels and wind turbines during the charging processes of electric motors.

R&D Investments: Increase investments in battery technology development and cost reduction.

Policy Support: Implement government incentives and regulations to promote the adoption of environmentally friendly technologies.

The use of electric motors in composite boats offers advantages in terms of environmental sustainability. Features such as lightweight, durability, and zero emissions make this technology indispensable for the future of maritime applications.

### 6.1. Recommendations

Use of Renewable Energy Sources: Promote the integration of solar and wind energy into the charging processes of electric motors.

Recycling Technologies: Increase research and development activities aimed at recycling composite materials and batteries.

Economic Incentives: Provide tax reductions and government subsidies to lower the costs of environmentally friendly boats.

Advantages of Composite Boats and Electric Motors: These boats play a crucial role in the future of marine transportation and recreation with their low carbon footprint, energy efficiency, quiet operation, and minimal environmental impact.

Renewable Energy Integration: Encourage the use of solar panels and wind turbines in conjunction with electric motors.

Material Recycling: Increase R&D efforts focused on the recycling processes of composite materials.

Economic Incentives: Implement government support and incentive programs to promote the adoption of environmentally friendly boats.

International Regulations: Develop international standards and certifications to enhance sustainability in the maritime sector.

Education and Awareness: Educate boat owners and professionals in the maritime sector about the advantages and ease of use of electric motors.

Infrastructure Development: Ensure the establishment of fast-charging stations at ports and tourist areas.

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# CHAPTER VIII

# HEAT TRACING METHODS FOR SHIP PIPELINES

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## Abstract

High-viscosity fluids, such as crude oil and heavy fuel oil, etc., transported by pipelines on ships, are heated to maintain their fluidity. Heat tracing methods are generally used for this process on ships. This study discusses the different heating methods used in ship pipelines. The two primary heating techniques highlighted are electrical and fluid (steam) heat tracing. Different electrical and steam heat tracing methods are explained, and the advantages and disadvantages of the methods are discussed. In addition, the factors to be considered when selecting heat tracing methods on ships are explained.

**Keywords:** Electrical heat tracing system, steam heat tracing, fluid heat tracing, ship pipeline, surface heating, tracer

## Introduction

Liquid-transport pipelines are susceptible to freezing when the temperature decreases. This results in slow-flow viscosity problems. If precautions are not taken, the pipe, valve, flange, and pipe support may crack or burst. This leads to expensive repairs, property damage, and downtime. Heat tracing technology resist changing weather conditions, prevent pipelines from freezing, and thus ensures smooth operation.

Heat tracing is a heating technology widely used in various industrial and commercial applications, such as ships, offshore platforms, petrochemical plants, power plants, water treatment plants, food processing plants, pharmaceutical production facilities, and storage and transportation systems. It offers reliable solutions for many applications requiring freezing and temperature control.

Heat tracing systems are generally divided into two categories: 1) Fluid, 2) Electrical. Steam is generally used as a heating fluid in ships. Therefore, the most commonly used applications on ships, such as electric and steam heat tracing, are described in this paper.

### *Literature on Electrical Heat Tracing (EHT)*

Baen (1993) and Sandberg et al. (2001) studied the control and monitoring of an EHT system. Brooks et al. (2000) analyzed 5 different control and monitoring methods to show that potential savings can be achieved for the EHT systems used in oil sands. Sandberg et al. (2002) discussed the development of control and monitoring methods for EHT systems.

Sandberg et al. (1996) performed finite element analysis on other pipeline equipment, such as valves and pipe supports. They reported the factors that can be used to estimate heat losses in such equipment.

Thompson et al. (1998) presented a methodology for reducing installation costs and increasing the reliability of EHT systems.

Chakkalakal et al. (2008) investigated a new electrical heating approach called “Electrical Gut Tracing” that can be used in pipelines. The advantages, disadvantages, reliability, and cost of the proposed method were compared with those of traditional electrical heat tracing methods. The applications of the proposed method were also identified.

Some practices that can be implemented to ensure the safe operation of EHT systems have been suggested by Baen et al. (1996). Existing standards and revisions to the EHT are described. Driscoll and Johnson (2009) studied design safety factors (DSF) in EHT systems and concluded that attention to DSFs has a direct impact on maintaining operation integrity.

Parikh et al. (2011) studied the design challenges of EHT systems in hazardous areas. They presented suitable methods for determining maximum sheath temperatures in gas environments.

Brazil et al. (2012) discussed the design parameters required to install EHT on uninsulated surfaces for reliable and efficient operation on ships and FPSO (Floating Production, Storage and Offloading) facilities in cold regions.

Lai et al. (2016) used EHT to prevent damage caused by frost in cold tunnels. The results confirmed the applicability of the proposed method to cold tunnels. The results suggest that thermal insulation is important for the success of proposed method.

### *Literature on Steam Heat Tracing (SHT)*

The method for designing a steam tracing monitoring system was described by Cotton (1960) and Risko (2019). Steiner (1976) developed a mathematical model that calculates the average and hottest point temperatures of the fluid inside steel pipes as functions of time. Practical tips for steam heat tracing system application were explained by Thomas (1999). The steam heat tracing methods were described by Pitzer et al. (2000).

The steam heat tracing system was theoretically modeled by Choi et al. (2021), who then developed a graphical user interface for selecting the steam heat tracing system.

In the past, steam tracing has been widely used in ship pipelines. However, with the advancement of technology, electrical heat tracing has also become a viable heat tracing method for ships. With the advent of highly reliable electrical heat tracing, the use of EHT systems on newly built ships has increased gradually.

The scope of this study is to understand heat tracing methods used in ship pipelines and to discuss their advantages and disadvantages. The methods are explained in Section 2. The advantages and disadvantages of the methods are discussed in Section 3. The factors to be considered when selecting a system are discussed in Section 4. The conclusions are presented in Section 5.

## 2. Heating Methods for Ship Pipeline

### 2.1 Electrical Heat Tracing (EHT)

Electric heat tracing is a modern system that uses electricity to generate heat. It prevents pipes, valves, flanges, pipe supports, tanks, and other components from freezing during cold weather. It is also employed to maintain a steady temperature. It is a great way to keep pipelines safe and sound. Thus, this modern heating solution offers reliable performance for many years. The electrical heat tracing system applied to the ship is shown in Fig. 1.

**Fig. 1** Application of an electrical heat tracing system on board.

The installation steps of the electrical heat tracing system are shown in Fig. 2.

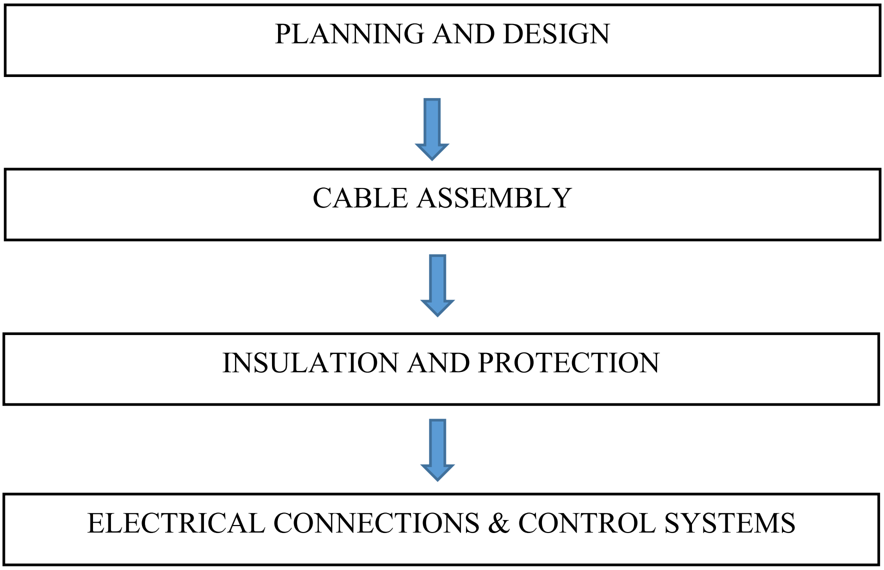


**Fig. 2** Installation steps of the electrical heat tracing system.

### *Planning and Design*

In the first stage, the heat trace system requirements are determined and an appropriate design is developed. This process includes determining the areas to be heated, calculating the temperature requirements, and selecting the appropriate cable type.

### *Cable Assembly*

The heating cables are installed in the pipeline or equipment after the design is completed. The cables are usually placed by wrapping or fixing them to the pipe surface. The most crucial thing to remember in this phase is that the cables should be positioned evenly and completely touching the pipe surface.

### *Insulation and Protection*

Pipelines or equipment are wrapped with appropriate insulating materials to reduce heat loss. Insulation lowers energy expenses while improving system efficiency. In addition, the insulation material protects the heating cables from physical damage.

### *Electrical Connection and Control Systems*

Electrical connections are made to the heating cables, and the control system is installed. Temperature sensors and thermostats are examples of components found in control systems, and they ensure that the system runs at appropriate temperatures. In addition to saving energy, these solutions ensure that the system operates safely.

Heating cables are used in various industrial areas. This demonstrates that a heating cable is a flexible and effective solution. Polymer-based cables are used in modern electrical heat tracing systems. These cables can modify the current flow based on the ambient temperature. A low ambient temperature causes more current to flow through the cables, which raises the temperature. Table 1 lists the factors to consider when selecting heat-tracing cables.

After determining the appropriate cable for the heat-tracing system to be used in the ship pipeline, the total cable length was calculated. In-line equipment, such as valves, flanges, and pipe supports, must be considered when determining the overall pipe length. After determining the pipe length, the correct thermostat control device and cable connection accessories should be selected.

**Table 1.** Considerations when selecting heat tracing cables.

| |
|---|
| It is necessary to use a certified cable that is appropriate for the area being used. |
| It is important to choose a cable that is appropriate for the highest exposure temperature. |
| The cable should be tested to ensure electrical integrity. |
| An appropriate cable for the required heat output should be selected. |
| The cable suitable for the desired fluid temperature should be selected. During selection, the cables' maintain temperature values are checked. |
| The thermal insulation thickness of the heating cable should be appropriately selected for the place of use. |
| The cable's temperature classification (T-code) needs to be considered. |
| It should be ensured that cables used in explosive, flammable, and easily flammable environments have ATEX certification. |

### 2.1.1 Types of Electrical Heat Tracing

There are generally two types of heat electrical tracing: constant wattage and self-regulating.

#### 2.1.1.1 Constant-Wattage Heat Electrical Tracing

The constant-wattage heat trace is a series circuit. Each trace has a fixed wattage. With this cable system, it is easy to predict the required output and amperage.

#### 2.1.1.2 Self-Regulating Heat Electrical Tracing

The self-regulating heat cables used in the electric heat trace system automatically adjust their power output to compensate for temperature changes. It is very difficult to judge exactly what the output will be on a heat-trace cable. Self-regulating heating cables are often preferred in ships and other industrial applications.

### 2.2 Steam Heat Tracing

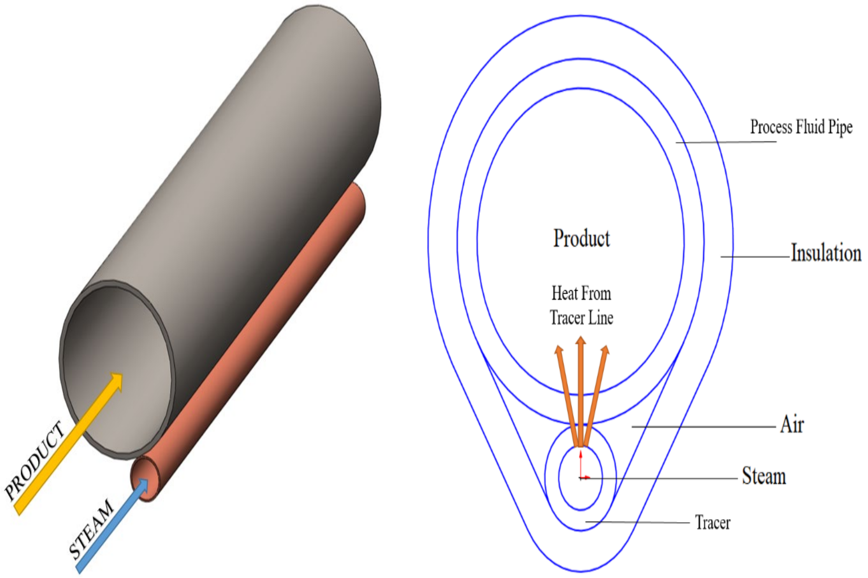
In steam heat tracing systems, the steam passes through a tube or small tube connected to the pipe to be heated. At the end of the process, the condensed steam is either sent to the boiler or discharged. Steam heating can be provided by waste heat generated on the ship, by burning fossil fuels, or by steam or electricity. Using steam that would otherwise be wasted is one way to maximize the efficiency of the steam tracing system.

The high latent heat of steam and the small amount of steam required for a large heating load make it an ideal fluid for heat transfer applications in ship pipelines. Steam can flow rapidly through the heat pipelines on board and flow to the point of use without pumping.

There are 3 different types of steam heat tracing systems: 1) external tube tracers, 2) cemented tracers, 3) steam jacketing (fully jacketed pipe).

#### *External Tube Tracers*

In the external tube tracer method, a pipe (tracer) is placed outside the pipe through which the main product line passes. The tracer can be placed on the main product line using different methods. It can be clipped or wired. When the temperature difference between the tracer and the product is low, the tracer can



be welded to the product line. The details of the external tube tracer method are presented in Fig. 3.

**Fig. 3** External tube tracers.

### *Cemented Tracers (Conduction Tracers)*

In this method, rapid heating is achieved by combining a tracer with sodium silicate and a carbon-containing cement in the main product line. Heat-transfer cement is used to increase thermal conductivity. The cemented steam tracing method is detailed in Fig. 4.

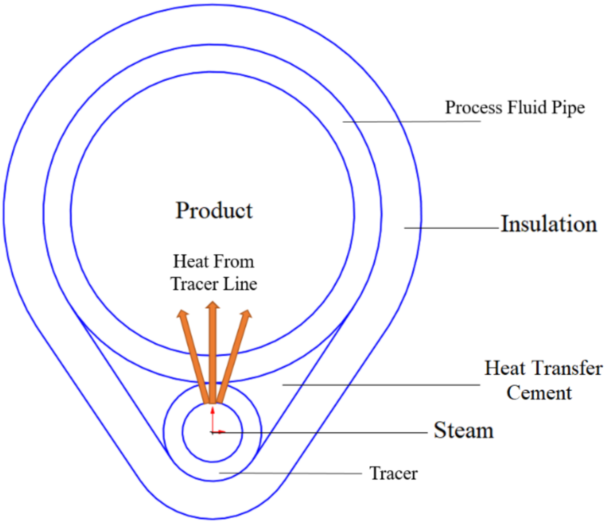


**Fig. 4** Cemented steam tracing.

### *Steam Jacketing (Fully Jacketed Pipe)*

A pipe larger than the diameter of the pipe through which the product passes is used, and this pipe (steam jacketed) surrounds the product pipe. Steam circulates in the annular region between the two pipes. Thus, the heating medium is in direct contact with the entire surface of the product pipe, ensuring maximum heat transfer. The steam jacketing method is illustrated in Fig. 5.

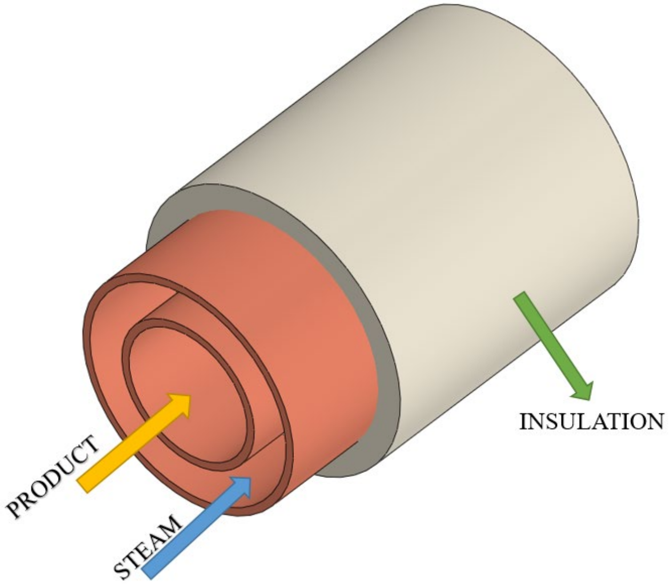


**Fig. 5** Steam jacketed pipe.

This method is used when the fluid temperature in the pipeline is close to the steam temperature. Steam jacketing method is expensive. It is used only in special cases with high heat demand and temperature control. The pipeline can be heated quickly using this method.

## 3. Comparison of Heat Tracing Methods

Leaks may occur in steam heat tracing systems. This leads to additional energy consumption. In addition, leaks must be stopped, and faulty pipes must be replaced. Repairs and replacements result in higher labor expenses. Therefore, the maintenance of the SHT system is more difficult than that of the EHT system. This situation in the SHT system increases the operational costs of the ship.

Waste heat from ships can be used in the SHT system. Thus, operational costs can be reduced. Therefore, it is logical to perform system selection by evaluating the total cost.

The installation of steam pipes on ships is more difficult than the installation of electrical cables. Therefore, the installation cost of the SHT system is higher than that of the EHT system.

The presence of temperature control devices in the EHT system ensured good temperature control. This allows the system to deliver very low and high heat outputs. Effective temperature control contributes to energy efficiency. In contrast, temperature control in the SHT system is more difficult. Therefore, the SHT system cannot be safely operated in situations in which precise temperature control is required.

Long pipes cannot be used in the SHT system because of steam condensation. On the other hand, heating cables of any length can be used in the EHT system.

The EHT system may pose a risk in parts of the ship where flammable materials are present. It may cause electric shock and ignition of flammable materials. Therefore, the SHT system is safer than the EHT system.

The advantages and disadvantages of the electric and steam heat tracing methods are presented in Table 2.

## 4. Selection of Heat Trace Solutions.

Energy efficiency and cost reduction are top priorities when selecting a cost-effective heat tracing system for ships. These factors should be evaluated when selecting a heat tracing system for ships:

- Cost
- Effectiveness
- The type of environment
- Environmental factors
- Reliability

When selecting a heat tracing system for ship pipelines, the capital, maintenance, and operating costs of the system should be evaluated together. The capital cost of the EHT system is higher than that of the SHT system. On the other hand, it is more difficult to install the SHT system in ship pipelines. In a country with high labor costs, the budget for installing the SHT will be substantial. In addition, the operational costs of the SHT and EHT systems on a ship depend on the operational conditions of the ship. The operational cost of the SHT system is generally higher than that of the EHT system. However, the use of waste heat in the SHT system on ships reduces operational costs. As a result, it would be appropriate to select the heat tracing system by collectively evaluating all the specified costs.

The heat tracing system should be selected based on the environment in which it will be used. The SHT is safer than the EHT system. The electrical cables and equipment to be selected for the EHT system must be determined according to the hazards of the environment in which they will be used. These hazardous environments are defined in the NEC (national electric code) standard. Materials suitable for the defined environments should be selected.

Environmental factors play an active role in selecting heat tracing systems. Factors such as whether the area is dry or wet, whether the environment is corrosive or not, and whether the components in the system will be exposed to mechanical impact play an important role in the selection of the system and materials.

Reliability is particularly important when selecting a heat tracing system for ships. Costs are important in system selection; however, if the interruption of the operation on the ship leads to a greater expense, the savings in upfront costs cannot be justified. Therefore, faults in heat tracing systems on ships should be of a size that can be repaired immediately or should not significantly hinder the operation of the system. The cables to be used in the EHT system on ships should be self-regulating heating cables. The failure of a single cable should not affect the entire heat-tracing system on the ship, and a cable selection should be performed accordingly.

The energy efficiency factor also plays an important role in selecting a heat tracing system for ships. Heat tracing systems should be evaluated in terms of energy efficiency and selected accordingly. Thus, significant contributions can be made to the ship energy efficiency and the decarbonization process.

**Table 2.** Comparison of the advantages and disadvantages of Electrical and Steam Heat Tracing Systems.

| **Heat Tracing Methods** | **Prons** | **Cons** |
|---|---|---|
| Steam Heat Tracing (SHT) | The unit energy cost of steam is low. | Leaks cause energy consumption. |
| | The condensate can be removed using a steam trap device. This feature provides a constant-temperature heat source. | Requires frequent repair and replacement. |
| | High heating rate and rapid warm-up | Additional labor costs are incurred for repair and replacement. |
| | Use of waste heat on ships | Cannot be used at extremely low or high temperatures. Lower temperature control level. |
| | Safer than EHT | Installation and maintenance are difficult compared to EHT. |
| | The operating costs of ships with low and medium pressure steam can be low. | The total energy cost is high. |
| | Low capital cost for high heat requirements | Obligation to use a short tracer |
| Electrical Heat Tracing (EHT) | Easy to control. Thus, better temperature control and much more efficient use of energy. | The unit energy cost of electricity is high. |
| | Installation and maintenance are easier than SHT. | Operating costs for EHT can be high compared to SHT on ships that use waste heat. |
| | The total energy cost of the EHT is also lower. | It may cause danger in parts of the ship where there are flammable materials. It may cause electric shock and ignition of flammable materials. |
| | Ability to provide very low and very high heat output | Overheating problems in cables when control is not done well. |
| | Ability to be used in non-metallic pipes | Low heating rate |
| | Remote temperature control and monitoring. | Slow warming up |
| | Use of long tracers. | |

## 5. Conclusion

In this study, the electrical and steam heat tracing systems used in ship pipelines are discussed. Heat tracing methods are of vital importance in ships, especially in winter, to prevent pipelines from freezing and to maintain the fluidity of high-viscosity fluids passing through the pipelines. Heat tracing provides both energy savings and minimizes operational interruptions by ensuring efficient ship operation.

Considering the energy efficiency and environmental concerns of ships, electrical and steam heat tracing systems should be considered critical subsystems that need to be monitored and controlled today.

The advantages and disadvantages of steam and electric heat tracing methods are also presented. Both methods have advantages and disadvantages. It is concluded that no ideal heat tracing method exists for all conditions. Steam and electric heat tracing techniques can be used for ships. The method should be selected by a collective assessment of the financial, environmental, energy efficiency, safety, and operating environment factors of the heat tracing system. Choosing the correct heat tracing method for ship pipelines and correctly designing the selected method will save energy. This will also make a positive contribution to the environment.

In the future, a study is planned to compare the capital, operating, maintenance, and total costs for low and high heat requirements and tracer lengths of two heat tracing methods used on ships.

## Acknowledgment

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# CHAPTER IX

# EVALUATION OF FUEL CELL TECHNOLOGIES AS AN ECO-FRIENDLY ENERGY SOLUTION IN THE SHIPBUILDING INDUSTRY

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## Abstract

Fuel cells provide an effective method for generating energy with their both high efficiency and low environmental impact. These systems hold significant potential for connecting clean energy approaches with sustainable practices in the shipbuilding industry. Offering both cleaner energy and operational efficiency, these technologies align with the shipbuilding industry's priorities. This chapter presents a comparative analysis of various fuel cell technologies in maritime applications, focusing on their advantages and disadvantages. Different types of fuel cells, including proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC), and molten carbonate fuel cells (MCFC), are analyzed for their relevance to maritime operations. The key aspects such as operational mechanisms, energy efficiency, fuel compatibility, and technological developments are examined in the maritime applications. The potential of fuel cells to lower environmental impact positions them as a valuable option for enhancing sustainability in the shipbuilding industry. As an alternative to conventional systems, fuel cells present a practical option for sustainable ship energy by balancing efficiency and environmental considerations. The broader adoption of these technologies is anticipated to contribute significantly to reducing carbon emissions in the maritime sector and advancing clean energy solutions.

**Keywords:** Fuel Cell, Energy Efficiency, Clean Energy, Shipbuilding Industry, Environmental Sustainability.

## Introduction

The growing focus on sustainability in the maritime industry has positioned fuel cell technologies as a valuable solution, offering high efficiency and lower environmental harm. Given the shipping industry's substantial contribution to global emissions, adopting cleaner energy sources to limit pollutants like $CO_2$, $NO_x$, and $SO_x$ is critical. By directly converting chemical energy into electricity without combustion, fuel cells provide a practical solution for shipbuilding industry, emphasizing quieter operations, lower emissions, and versatile fuel options. The adoption of fuel cell technology supports the maritime industry's transition to greener operations and aligns with evolving regulatory requirements. The shipbuilding industry is facing tighter restrictions on carbon emissions and pollutants. The Third IMO GHG Study (2014) reported that international shipping was responsible for 800 million tons of $CO_2$ in 2012, making up 2.2% of global emissions. According to Fan et al. (2018), ship emissions accounted for 15% of $NO_x$ and 13% of $SO_x$ globally in 2012. Such significant emission levels have motivated the maritime industry to transition to cleaner energy technologies. The International Maritime Organization (IMO) has enforced stricter emission standards for NOx and SOx under the MARPOL Annex VI framework (Ling-Chin and Roskilly, 2016; Moreno-Gutiérrez et al., 2019). With conventional diesel engines struggling to meet these stringent standards, alternative solutions like fuel cells are gaining attention for their ability to lower emissions and enhance efficiency.

Proton Exchange Membrane, Solid Oxide, and Molten Carbonate Fuel Cells (PEMFC, SOFC, and MCFC) are the primary fuel cell technologies utilized in maritime applications. With their low-temperature operation and high power output, PEMFCs are especially efficient when utilizing hydrogen as a fuel source. With the capability of operating at high temperatures, SOFCs can efficiently use a range of fuels, including ammonia and low-sulfur diesel. MCFC systems are notable for their capacity to efficiently process carbon-based fuels at high temperatures, contributing to $CO_2$ emission reduction (Yan et al., 2020; Sohani et al., 2020). In cases of significant power demands and limited feasibility of hydrogen storage, SOFC and MCFC systems provide suitable alternatives (Inal, 2022).

PEMFC systems have been effectively implemented across various maritime projects. As part of the ZEMSHIP project, a zero-emission passenger vessel was built in Hamburg, equipped with two 48 kW PEM fuel cells and a 560V battery system (Schneider et al., 2010; Vogler and Würsig, 2011). The ship demonstrated over 2,500 hours of operation while achieving an annual CO2 emission reduction of 47,000 kg compared to diesel-electric systems. A 165 kW PEMFC system was successfully deployed on a research vessel in the MARANDA project, highlighting its capability in Arctic environments. Within the DESIRE project, hydrogen production via a diesel reformer for PEMFCs was developed and successfully applied on a naval vessel (Krummrich et al., 2006). The ISHY and H2SHIPS projects have also contributed to understanding the feasibility and application of PEMFC technology in the shipbuilding sector. An aluminum ferry powered by 41 PEM fuel cell units, each producing 120 kW, was designed under the SF-BREEZE project, emphasizing the role of PEMFC technology in the maritime transport sector (Pratt and Klebanoff, 2016). In the Pa-X-ell project, a methanol reformer integrated with high-temperature PEM fuel cells demonstrated lower emissions and effective power and heat production on a passenger vessel (Tronstad et al., 2017).

The use of SOFC systems in maritime applications has yielded encouraging outcomes. In the METHAPU project, a 20 kW SOFC unit fueled by methanol was tested on a RoRo vessel, achieving over 700 hours of continuous operation (Tronstad et al., 2017). A commercial SOFC system developed under the SchIBZ project demonstrated power outputs of 50–500 kW and 50% efficiency using low-sulfur diesel (Leites et al., 2012; e4ships, 2022). Furthermore, LNG-powered SOFC technologies, as explored in the PACBOAT and NAUTILUS (Nautical Integrated Hybrid Energy System for Long-haul Cruise Ships) projects, have proven suitable for large-scale cruise ship applications. The FELICITAS project utilized a 250 kW SOFC system to enhance efficiency while reducing hazardous emissions, providing over 60% efficiency and confirming the feasibility of SOFCs for maritime applications (FELICITAS, 2009).

Applications of MCFC systems in shipbuilding industry have been extensively evaluated. The FellowSHIP project equipped the Viking Lady with a 320 kW LNG-fueled MCFC system, which successfully operated for more than 18,500 hours without emitting NOx, SOx, or particulate matter (Inal and Deniz, 2018; McConnell, 2010; Tronstad et al., 2017). The MC-WAP project investigated a 150-kW diesel-fueled MCFC system, highlighting its ability to harness exhaust gases for supplementary power through high-temperature operation. MCFC applications in ship services were explored in the SSFC (Ship Service Fuel Cell) and FCSHIP (Fuel Cell Technology for Ships) projects, underlining their potential to enhance efficiency and reduce environmental impacts (Allen et al., 1998; Privette et al., 2002; Bourne et al., 2001; Alkaner and Zhou, 2006).

This chapter focuses on assessing the applicability of Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), and Molten Carbonate Fuel Cells (MCFC) in shipbuilding industry. The analysis considers critical performance factors, including power density, power capacity, operating temperature, fuel flexibility, efficiency, environmental impact, physical size, lifetime and cost. The study offers a comprehensive investigation regarding the suitability and implementation potential of these technologies for various types of ships. By examining the strengths and limitations of various fuel cell types, this analysis aims to support the development of future plans for their integration into shipbuilding processes, contributing to a more sustainable and efficient industry.

## Comparative Analysis of PEMFC, SOFC, and MCFC Fuel Cell Technologies

A detailed examination of the key characteristics and technical properties of PEMFC, SOFC, and MCFC systems is presented in this section. Due to their flexibility and wide applicability, PEMFCs are considered among the leading fuel cell types for large-scale implementation (Sharaf and Orhan, 2014). Operating at low temperatures ranging from 60 to 180°C, PEMFCs use an ion-exchange membrane that facilitates proton conduction while serving as an electrical insulator (Tronstad et al., 2017). Maintaining sufficient humidity is crucial for the membrane's performance, as it enables efficient proton movement. Hydrogen is the main fuel for PEMFCs, reacting with oxygen to generate water, electricity, and heat in an exothermic process. With efficiencies ranging from 40 to 60%, PEMFCs are known for their flexible operation, simple water management, and low material requirements. Despite their benefits, PEMFCs depend on platinum-based catalysts, which are vulnerable to impurities such as carbon monoxide, leading to catalyst poisoning (Baschuk and Li, 2001). Equations 1, 2, and 3 illustrate the electrochemical processes occurring within PEMFC systems (Mench, 2008). An outline of the primary characteristics of PEMFC is provided in Table 1 (Ebrahimi et al., 2021; Inal and Deniz, 2018; Sharaf and Orhan, 2014; Tronstad et al., 2017). Figure 1 shows a visual representation of the structural components of a Proton Exchange Membrane Fuel Cell.

$$H_2 \rightarrow 2H^+ + 2e^- \text{ (Anode)} \tag{1}$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \text{ (Cathode)} \tag{2}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \text{ (Total)} \tag{3}$$

**Table 1.** Characteristics of PEMFC (Ebrahimi et al., 2021; Inal and Deniz, 2018; Sharaf and Orhan, 2014; Tronstad et al., 2017)

| Parameter | Value |
|---|---|
| Electrolyte | Proton Exchange Membrane |
| Temperatures | 60 – 180 °C |
| Efficiency | %40-60 |
| Fuel Options | Hydrogen |
| Emissions | Water |

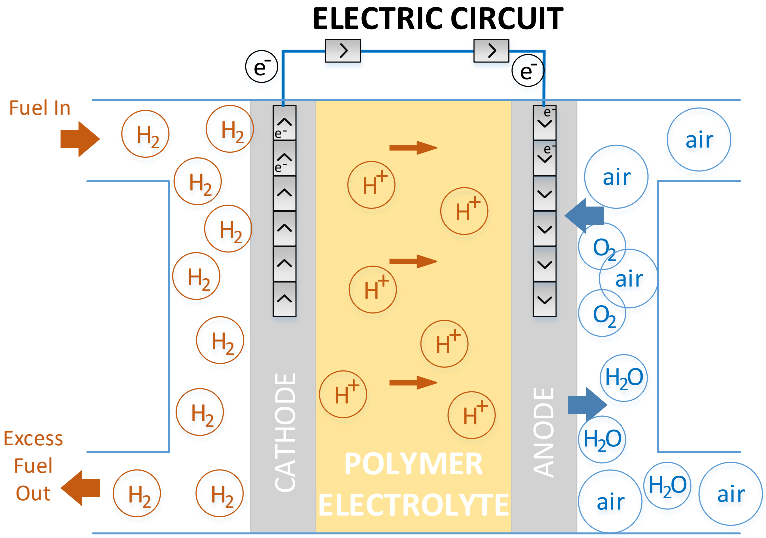

**Figure 1.** Schematic representation of PEMFC.

Solid Oxide Fuel Cells (SOFCs) are categorized as high-temperature fuel cells, with typical operating ranges between 800 and 1000°C (Marefati and Mehrpooya, 2019; Mench, 2008). In SOFC systems, a solid-state electrolyte made from yttrium-stabilized zirconia facilitates the conduction of oxygen ions at these high temperatures (Tronstad et al., 2017). The fast electrochemical reaction kinetics enabled by the high temperatures of SOFCs contribute to their electrical efficiencies, typically between 40% and 70%. SOFCs are ideal for combined heat and power (CHP) systems due to their high operating temperatures, achieving overall efficiencies of 75-80% (Tronstad et al., 2017). The internal reforming capability of SOFCs enables the direct use of LNG, methanol, and hydrogen as fuels, bypassing the requirement for external reformers. The ability to utilize various fuels provides SOFCs with a substantial advantage for maritime applications. Despite their advantages, SOFCs face challenges including prolonged startup times, the requirement for effective thermal insulation and material degradation due to thermal cycling. Equations 4, 5, and 6 outline the electrochemical processes fundamental to SOFC operation (Mench, 2008). The main attributes and specifications of SOFC systems are outlined in Table 2 (Sharaf and Orhan, 2014; Tronstad et al., 2017). Figure 2 illustrates the structural design and operational components of a Solid Oxide Fuel Cell.

$$H_2 + O^{-2} \rightarrow H_2O + 2e^- \text{ (Anode)} \qquad (4)$$

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{-2} \text{ (Cathode)} \tag{5}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \text{ (Total)} \tag{6}$$

**Table 2.** Characteristics of SOFC (Sharaf and Orhan, 2014; Tronstad et al., 2017)

| **Parameter** | **Value** |
|---|---|
| Electrolyte | Ceramic that conducts oxide ion |
| Temperatures | 800 – 1000 °C |
| Efficiency | %40-70 |
| Fuel Options | Natural Gas, Diesel, Hydrogen |
| Emissions | $CO_2$ (with carbon included fuel) |

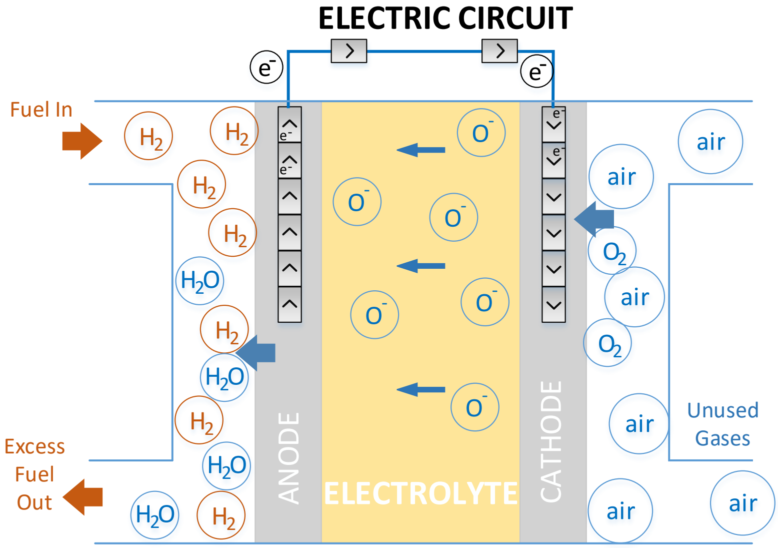

**Figure 2.** Schematic representation of SOFC.

Molten Carbonate Fuel Cells (MCFCs), operating in the temperature range of 600-700°C, facilitate efficient ion conductivity and eliminate the reliance on high-cost catalysts like platinum (Marefati and Mehrpooya, 2019). The electrolyte in MCFCs consists of molten alkali metal carbonates, with nickel serving as the anode material and nickel oxide as the cathode material (Mench, 2008). With operating temperatures of 600-700°C, MCFCs achieve electrical efficiencies between 50-60%, which can rise to approximately 85% in combined heat and power systems (Tronstad et al., 2017). By reforming fuels such as natural gas, diesel, and hydrogen directly within the cell, MCFCs offer improved fuel flexibility and avoid the need for external reformers. While MCFCs offer many advantageous, drawbacks such as a slow startup process, lower power density, and high-temperature corrosion and material cracking (Inal, 2022). MCFCs are commonly utilized in high-energy-demand scenarios, including industrial power production and large-scale maritime applications, due to their fuel versatility and exceptional efficiency. Equations 7, 8, and 9 illustrate the electrochemical mechanisms fundamental to MCFC operation (Mench, 2008). Table 3 highlights the primary features of MCFC systems (Sharaf and Orhan, 2014; Tronstad et al., 2017). Figure 3 illustrates the operational design of a Molten Carbonate Fuel Cell.

$$H_2 + CO_3^{-2} \rightarrow H_2O + CO_2 + 2e^- \text{ (Anode)}$$

$$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{-2} \text{ (Cathode)}$$

$$H_2 + \frac{1}{2}O_2 + CO_2 \rightarrow H_2O + CO_2 \text{ (Total)}$$

**Table 3.** Characteristics of MCFC (Sharaf and Orhan, 2014; Tronstad et al., 2017)

| **Parameter** | **Value** |
|---|---|
| Electrolyte | Molten mixture of alkali metal carbonates |
| Temperatures | 600 – 700 °C |
| Efficiency | %50-60 |
| Fuel Options | Natural Gas, Diesel, Hydrogen |
| Emissions | $CO_2$ (with carbon included fuel) |

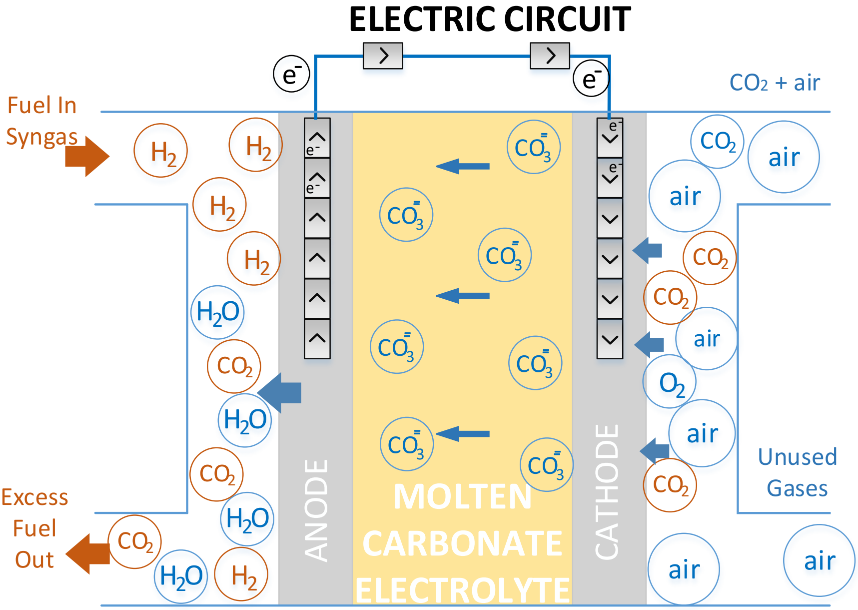

**Figure 3.** Schematic representation of MCFC.

## A Comparative Study of PEMFC, SOFC, and MCFC Systems in Shipbuilding

This section provides a comparative evaluation of PEMFC, SOFC, and MCFC systems based on their performance characteristics. Power density, power capacity, environmental impact, operating temperature, fuel flexibility, efficiency, operating temperature, physical size, cost and lifetime are considered as performance parameter. A detailed investigation is conducted into the applicability of fuel cell systems for various ship types based on their performance metrics.

The efficiency of fuel cell systems varies according to their type and operational conditions. With electrical efficiencies of 50-60%, PEMFCs are particularly effective for converting hydrogen directly into electricity (Tronstad et al., 2017). The low-temperature operation of PEMFCs (50-100°C) reduces their effectiveness in CHP systems, where higher waste heat is necessary for further energy recovery (Dai et al., 2009). With operational ranges of 500-1000°C for SOFCs and 600-800°C for MCFCs, these systems leverage high temperatures to efficiently utilize waste heat (Mench, 2008). When combined with CHP systems, SOFCs achieve efficiencies of 70-80%, while MCFCs reach up to 85%, offering significant advantages in scenarios where both power and heat are needed (Tronstad et al., 2017; De-Troya et al., 2016).

Operating temperature plays a critical role in determining the performance and suitability of different fuel cell systems. With low operating temperatures, PEMFCs provide quick start-up times and simplified thermal management, making them available for applications demanding fast responses. The low-temperature nature of these systems heightens their vulnerability to fuel impurities, demanding the use of pure hydrogen (Baschuk and Li, 2001). SOFCs and MCFCs stand out for their ability to use a wide range of hydrocarbon fuels directly, thanks to their high-temperature operation, without relying on external reformers (Tronstad et al., 2017; Marefati and Mehrpooya, 2019). Although their fuel flexibility is improved, SOFCs and MCFCs face longer start-up times and require advanced thermal management to withstand the heat (Tronstad et al., 2017). An overview of the performance metrics, including fuel flexibility, operating temperature, and efficiency for PEMFC, SOFC, and MCFC, is provided in Table 4 (Tronstad et al., 2017).

**Table 4.** Overview of efficiency, operating temperature, and fuel flexibility for PEMFC, SOFC, and MCFC systems (Tronstad et al., 2017).

| **Parameter** | **PEMFC** | **SOFC** | **MCFC** |
|---|---|---|---|
| Efficiency | %50-60 (electrical) | %60 (electrical)<br>%70-80 (with heat recovery) | %50 (electrical)<br>%85 (with heat recovery) |
| Operating Temperature | 50-100 °C | 500-1000 °C | 600-800 °C |
| Fuel Flexibility | Hydrogen | LNG, Methanol, Diesel, Hydrogen | LNG, Methanol, Diesel, Hydrogen |

The capacity to operate with diverse fuels, including hydrogen, LNG, diesel, and ammonia, is a key advantage of SOFCs and MCFCs (van Biert et al., 2016; De-Troya et al., 2016). In shipbuilding applications, this fuel flexibility enhances their adaptability to varying fuel availability and economic considerations. Unlike SOFCs and MCFCs, PEMFCs depend largely on high-purity hydrogen, which restricts their flexibility (Baschuk and Li, 2001). The need for external reforming when using hydrocarbons makes PEMFCs less suitable for applications requiring diverse fuel types (Sasank et al., 2016).

The size and power density of fuel cell systems vary significantly depending on their type. High power density is a defining feature of PEMFCs, offering specific power between 125 and 750 W/kg and power densities of 50 to 400 W/L (van Biert et al., 2016). Their suitability for compact spaces positions PEMFCs as a preferred option for smaller vessels and auxiliary power sources on larger ships. An example is the PEMFC model "FCe 150," which generates 150 kW of power within a compact 0.66 $m^3$ volume, highlighting its efficiency for transport use (Minnehan and Pratt, 2017). High operating temperatures and insulation demands contribute to the lower power densities observed in SOFCs and MCFCs compared to PEMFCs (Mench, 2008). High-temperature systems, such as MCFC and SOFC, need extra fuel processing equipment for diesel or LNG, leading to increased volume and mass (Inal, 2022). The SureSource 3000 MCFC model delivers 2800 kW of power while occupying a substantial volume of 252 $m^3$ (Minnehan and Pratt, 2017). These systems are more appropriate for large ships, including cargo and special-purpose vessels, where space constraints are less significant.

The environmental impact of PEMFCs is minimal, as they emit only water when using hydrogen, making them the cleanest among the three (Tronstad et al., 2017). SOFCs and MCFCs emit $CO_2$ during operation with carbon-based fuels, but their environmental impact is significantly less than diesel engines (Bourne et al., 2001). The high operating temperatures of SOFCs result in minimal $NO_x$ emissions, but auxiliary processes, such as heated fuel reformers or burners, can produce small quantities. MCFCs' ability to recover and reuse $CO_2$ from fuel streams offers significant opportunities for advancing carbon capture systems (Tronstad et al., 2017). Table 5 summarizes the power capacity, emissions, physical size, and relative cost attributes of PEMFC, SOFC, and MCFC systems.

**Table 5.** Overview of power density, emissions, size, and relative cost for PEMFC, SOFC, and MCFC systems (Tronstad et al., 2017).

| Parameter | PEMFC | SOFC | MCFC |
|---|---|---|---|
| Power Capacity | Up to 120 kW | 20-60 kW | Up to 500 kW |
| Emissions | No | CO2 and low levels of NOX (with carbon fuel) | CO2 and low levels of NOX (with carbon fuel) |
| Physical Size | Small | Medium | Large |
| Relative Cost | Low | High | High |

The economic aspect of fuel cells is a key consideration in their potential for widespread implementation. The use of platinum catalysts makes PEMFCs more expensive by increasing both the cost of materials and production. In addition, PEMFCs demand high-purity hydrogen along with sophisticated storage and handling systems, which increase their overall cost. Technological advancements and larger-scale production are anticipated to lower the cost of PEMFCs over time (Tronstad et al., 2017). While SOFCs and MCFCs require high initial investments due to complex and high-temperature components, they offer promising long-term benefits. These technologies can operate with a variety of fuels, including biogas and natural gas, enabling potential fuel savings. Cost advantages are expected in the long run for these systems, thanks to their higher efficiency and capability to integrate CHP applications, which reduce operating costs (van Biert et al., 2016).

High operating temperatures negatively affect the durability of fuel cells by inducing thermal stresses that shorten their lifespan (Dodds et al., 2015). Recent improvements in SOFCs have led to lifespans of 40,000 to 80,000 hours, and occasionally as high as 90,000 hours (Ellamla et al., 2015). Due to their high-temperature design and corrosive electrolytes, MCFCs have shorter lifespans, typically ranging from 15,000 to 30,000 hours (Elkafas et al., 2022). The lifetime of PEMFCs in stationary applications ranges from 60,000 to 80,000 hours, with stack replacement intervals of 20,000 to 30,000 hours. For transport applications, PEMFCs typically offer lifespans beyond 25,000 hours (Ellamla et al., 2015; Staffell, 2015). In maritime operations, where vessels operate 4,000 to 6,500 hours annually, stack replacement plays a major role in long-term cost management.

## Conclusion

This section provides a detailed evaluation of Proton Exchange Membrane Fuel Cells, Molten Carbonate Fuel Cells, and Solid Oxide Fuel Cells, the most widely used fuel cells in the maritime sector, based on specific performance criteria. Performance evaluation focused on the parameters such as power density, power capacity, operating temperature, environmental impact, physical size, efficiency, lifespan, and cost. Based on the outcomes of these assessments, recommendations have been proposed to identify the ship types most suitable for PEMFC, SOFC, and MCFC systems, considering their features in relation to performance criteria.

Proton Exchange Membrane Fuel Cells (PEMFCs) offer a combination of low operating temperatures and high electrical efficiencies, typically ranging from 50-60%. Due to their fast start-up capabilities and high-power density, they are especially well-suited for short-range vessels and smaller ships like ferries, passenger vessels, RO-RO ships, and small craft, where weight and space constraints are critical. PEMFCs are particularly well-suited for auxiliary power units (APUs) and distributed generation in maritime applications due to their ability to operate efficiently at low power levels. However, their low operating temperature results in limited waste heat production, reducing the practicality of integrating PEMFCs with combined heat and power (CHP) systems. Additionally, the reliance of PEMFC systems on high-purity hydrogen necessitates the use of external reformers when hydrocarbons are employed, increasing both operational complexity and costs. The specific features of PEMFCs make them an optimal choice for short-distance vessels or those not requiring continuous high power output, especially in settings where hydrogen storage systems are established.

Molten Carbonate Fuel Cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs) are both highly applicable to large-scale maritime operations, with their specific applications differing based on technical features and operational demands. MCFCs operate at temperatures of 600-800°C and provide flexibility in fuel options, including hydrogen, methanol, and hydrocarbons, which makes them a practical choice for long-distance commercial operations. The capability to efficiently utilize hydrocarbon fuels without relying on extensive hydrogen storage infrastructure makes them an ideal solution for container vessels, large cargo ships, and tankers, where fuel availability and long-distance efficiency are critical. MCFCs also offer the potential to capture and reuse carbon from the fuel stream, contributing to environmental sustainability and helping meet stricter maritime emissions requirements. However, the corrosive properties of the molten electrolyte result in a shorter operational lifespan for MCFCs compared to SOFCs, causing faster degradation and increased maintenance expenses.

Known for their high operating temperatures (500-1000°C), SOFCs exhibit exceptional fuel flexibility by directly utilizing fuels such as hydrogen, methanol, and natural gas, avoiding the requirement for external reformers. This capability makes them highly suitable for vessels operating over long distances with continuous power demands. SOFCs can recover waste heat efficiently due to their high operating temperature, which supports integration into CHP systems, leading to overall efficiencies of up to 70-80%. By combining high efficiency with the ability to supply both electricity and heat, SOFCs are particularly well-suited for ships such as cruise liners, large cargo vessels, and offshore support ships that require continuous high power. While slower start-up times and complex thermal management are challenges for SOFC systems, their long operational life, lasting up to 80,000 hours, ensures they are a reliable long-term solution for large vessels covering extensive distances.

This research conducts a comprehensive review of Proton Exchange Membrane Fuel Cells, Molten Carbonate Fuel Cells, and Solid Oxide Fuel Cells, which play a significant role in shipbuilding operations. This research provides valuable insights, particularly for researchers specializing in the application of fuel cell systems for various types of ships. This research can be expanded in the future by exploring different performance metrics, modelling fuel cell applications in greater detail for various ship designs, and carrying out advanced engineering analyses.

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