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Challenges and Opportunities in Harmonizing MARPOL Annex VI (Air Pollution) with IMO 2050 Emission Targets

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Abstract: Marine transportation is a critical component of the global economy, yet a major source of SOx and NOx emissions, causing air pollution. These emissions have adverse effects on the environment and human health, which has led to the management body, the International Maritime Organization (IMO), putting in place the MARPOL Annex VI regulation. This paper examines the major issues and gaps to analyze critical aspects of how the IMO 2050 emission can be achieved under the MARPOL Annex VI framework. Survey results from maritime professionals provide insight into main concern areas: high implementation costs of new technologies, insufficient infrastructure of alternative fuels, variation in enforcement depending on region, low penetration and training, and the absence of monitoring indicators. The results revealed that the aforementioned challenges correlate with the activity of global frameworks like the BA to standardize check and balance mechanisms under MARPOL Annex VI. To this end, the study highlights the roles of international cooperation, technologies, and capacity-development endeavors to fill these gaps. It is when performing its operations, using the mechanisms for the uniform enforcement of standards, and training, key principles facilitating compliance and thus decreasing the number of emissions from ships are seen. This research therefore, aids in the aimed discussion of sustainable shipment and offers valuable information to policymakers, regulatory agencies, and involved parties that seek to attain the IMO 2050 goals and embrace green shipping.

Keywords: *MARPOL Annex VI, Sustainability, IMO 2050 target, Challenges.*

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I. INTRODUCTION

A. Background

Maritime transport about 90% of the world's commodities by volume and is an essential component of the global economy, however, it is an extensive source of air pollution and GHG emissions. As a result of the increase in interest in climate change, countermeasures have been laid down over the years through the international regulation of shipping. One such framework is the International Maritime Organization's (IMO) MARPOL Annex VI which covers issues of air pollution by regulating emissions of SOx, NOx, and PM from ships.

MARPOL Annex VI entered into force in 1997, and the measures have been implemented since 2005; however, the regulation has been amended several times, increasing emission standards of vessels gradually. It also supports a shift in the usage of better energy-saving technologies to enhance clean shipping. However, new emissions challenges and opportunities were introduced by the International Maritime Organization (IMO) emission targets introduced in 2018 with the desired goals set for 2050. These targets include the intent to lessen the emissions of international shipping by at least 50% by 2050 with the reference figure being 2008 and would enfold significant cuts in the carbon dioxides (CO2), a primary cause of climate change.

The regulation process that is going to be followed to achieve IMO 2050 with regard to MARPOL Annex VI is not very simple, as it involves immediate reduction of Air Pollutants and at long-term reduction of GHG (Kalamo, 2018). The first one is rooted in the fact that whereas MARPOL Annex VI deals with regulating pollutants including SOx and NOx, the IMO 2050 targets are based on reducing GHG emissions. Filling this gap appears to call for shifts in policy approaches and technologies simultaneously.

This research will evaluate MARPOL Annex VI in terms of coverage, measures of implementation and compliance, and compliance with IMO 2050 targets. These are regulatory barriers, whereby the current laws do not provide sufficient provisions for future objectives, technical barriers where the availability of emissions-cutting technologies prove to be a problem and economic barriers,

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whereby the costs of implementing new technologies and practices prove steep.

Nevertheless, there are considerable prospects for the compatibility of the two frameworks despite the differences listed above. Milestones in technology, including different fuels (hydrogen, ammonia, biofuels), energy-efficient propulsion, techniques and carbon handler technologies are the potential to diminish emissions. Besides, shifting policies, such as the one entering the market-based mechanism and improving the compliance level of releasing regulations, can enhance the transition to a more sustainable maritime industry (Dewan & Godina, 2023)

There is complexity as well as the prospect of harmonizing MARPOL Annex VI with the IMO 2050 emission targets are. When it comes to the key issue of regulating emissions from the international maritime industry, the three issues of regulation concern, technical and economical solutions that can transform an industry for it to become sustainable have to be addressed, together with the technological and policy changes to create a more sustainable environment for the international maritime industry. This research aims at uncovering this complexity and making recommendations on how the industry can manage this important transition effectively.

B. Problem Statement

The maritime industry has been shown to play a leading role in international commerce business. Also, it contributes to air pollution through gases from SOx, NOx, PM, and CO2 emissions by ships. To regulate emissions from ships, the IMO adopted MARPOL Annex VI to limit emissions from ships. However, setting 2050 emission targets in the IMO introduces new problems: trying to cut the total GHG emission from international shipping by at least 50% by 2050.

As it stands, MARPOL Annex VI targets the limitation of sort SOx, NOx, particles and other traditional air pollutants from ships but is not as comprehensive for regulating the long-term emissions of tangible amounts of CO2 as are IMO 2050 targets. This gap means that while achieving higher levels of abatement invariably results in reduced air pollution, policymakers and industry players seeking to address air pollution must also look at other general climate mitigation objectives and plans, reviewed above.

Technology is much of a challenge when it comes to the standardization of these frameworks. Current ships and propulsion technologies conform to MARPOL Annex VI, but they do not address emissions of CO2 which are at the center of the IMO 2050 goals. Many emissions-reducing fuels such as hydrogen, ammonia, and biofuels have limitations that are associated with infrastructure, safety, and cost.

The economic consequences of bringing MARPOL Annex VI into compliance with the goals of the IMO 2050 are large. Globally, the maritime industry is deeply capital-intensive, and the transition toward low-carbon or even zero-emission solutions is expensive. The case has it that shipowners and operators may fail to meet pollution and climate change objectives due to a lack of economic incentives or market signals.

II. OBJECTIVES

- To assess the current application of MARPOL Annex VI related to air pollution and compare it with IMO 2050 emission targets.
- To find the main challenges in aligning MARPOL Annex VI with IMO 2050 targets, including economic and operational barriers.
- To find opportunities for enhancing MARPOL Annex VI to meet better IMO 2050 emission targets, including technological innovations and policy adjustments.

A. SCOPE

The shipping industry is one of the largest in emitting pollutants to the environment and the climate of our planet. MARPOL Annex VI was developed by the International Maritime Organization (IMO) to regulate the emission of air pollution from ships, especially SOx, NOx, and particulate matter. However, which has are up new challenges and opportunities. IMO's 2050 emission targets seek to achieve at least 50 percent cuts in greenhouse gases (GHG) by 2050. Namely, this research aims to fill the existing research gap, which concerns the adequacy of the present levels of control measures of air pollution under the MARPOL Annex VI to address the long-term vision of the IMO 2050 strategy.

The current scope of MARPOL Annex VI, established only in 1997 addresses only traditional air emissions and does not embrace the need for GHG cuts embraced by IMO 2050. It is the purpose of this research to examine these challenges in detail including the shortcomings of existing regulations and the technological and economic constraints involved.

The study also looks at possibilities of technological advancement and policy change of the Sea transportation industry. Other promising solutions, like low-carbon fuels, energy-efficient ship designs, and carbon capture systems present large potential in achieving reduced emissions but are not implemented on large-scale basis due to factors like costs, infrastructural development, and approval.

B. Relationship of the Study with Sustainable Development Goals (SDGs)

The shipping industry is an important part of the UN Sustainable Development Goals, particularly on issues to do with the environment and climate change. This research links regression analysis to MARPOL Annex VI of the International Maritime Organization with the IMO 2050 emission targets that address climate change for sustainability, innovation, and partnership worldwide. Some of the goals are closely related to the maritime industry, namely carbon capture from the atmosphere, air pollution, climate change adaptation, affordable and clean energy, and consumption and production, partnership. (Dewan & Godina, 2023)

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SDG 13, which calls for more action on climate issues, and the IMO emission ambitions for this year 2050 align with this goal. The current study seeks to decrease CO2 emissions by establishing the obstacles and potential for the industry in minimizing GHG emissions and studying technological advancements. SDG 14 sustains natural society through the emission control of air pollutants, while on the other side, SDG 9 deals with the infrastructural strength, industrialization, and innovations. The study also looks at sustainable resources in maritime business and reduced consumption and production, dialogues, and participation of actors in the transport system.

III. METHODOLOGY

The analysis in this chapter presents a systematized methodology to explore the issues and perspectives of aligning MARPOL Annex VI Air Pollution and IMO 2050 emission goals. Due to the nature of the research questions, the data was collected through a mixed methodology, where quantitative data was also collected to have a more comprehensive way of analyzing the current state of regulations and practices and the challenges to meeting the IMO 2050 targets. This chapter presents a description of the research design, source of data, methods of data collection, and data analysis.

A. Research Design

This study used surveys and thematic analysis from past research to formulate the research design for this study. The combination of qualitative and quantitative research made it possible to investigate the specific issues of regulatory legislation and professional opinions and to combine these results with the outcomes of past studies.

The research methodology employed in the study is exploratory and descriptive in nature, considering that the study aims to evaluate the provisions of MARPOL Annex VI at the present time, determine the difficulties that may exist in relation to the components of the IMO 2050 strategy, and outline steps for their improvement. The descriptive part identified the current legislation and the standards of emissions, the exploratory part focused on possible ways of improving MARPOL Annex VI for the identified long-term environmental goals.

B. Data Sources

Sources of data for this study included both primary and secondary sources to get the information on challenges facing MARPOL Annex VI, air pollution by ships, and IMO 2050 emission goals. Literature review was done from the scholarly materials (Google Scholar, Science Direct, and Research Gate) that include peer-reviewed journals from the fields such as maritime, environmental, and regulatory policies. Industry reports shed light on the existing practices, new technologies that are being adopted, and current policies in the industry.

Primary data was collected using structured questionnaires administered to major shippers, shipping associations, environment regulating bodies, and non-governmental organizations, as well as subject matter specialists. This project was undertaken a discuss past studies in order to establish an appreciation of the dynamics involved in matters of regulation and technology within the maritime industry.

C. Secondary Data Sources

Thematic analysis of existing research on maritime emissions, MARPOL Annex VI regulation, and IMO 2050 targets helps in understanding the current legislations, technologies and problems confronted in the context of the shipping industry. SHIPINDEX is an online repository of industry reports from Maritime organizations, shipping companies and environmental non-governmental organizations offering information on the MARPOL Annex VI compliance and emission status. Different IMOs legislative documents also state about the strategies for IMO to meet 2050 goals. MARPOL Annex VI and corresponding climate change legislation are discussed, as well as international, regional, and national statutes addressing air pollution in the global maritime industry.

IV. DATA COLLECTION METHODS

A. Literature Review

Secondary data was collected through a literature review for MARPOL Annex VI and IMO 2050 targets. The major points of concern of the regulation were also be highlighted together with the significant technologies to be covered by the review and the major issues relating to the reduction of maritime emissions. This gave a theoretical framework of the study and background information, and understanding of the issue under consideration.

B. Instrument

Questionnaires were devised to obtain quantitative data from the large number of respondents representing distinct maritime sectors. The survey consisted of structured questions that addressed: MARPOL Annex VI and IMO 2050 emission awareness and understanding amongst the operating companies. The perceived difficulties in compliance with existing regulatory requirements on air pollution levels. The technical and procedural revolutions are needed to gear up for future emissions goals. Attitudes toward possible directions for positive changes or additions to regulatory barriers. To maintain maximum objectivity of the survey and to allow for an effective quantitative analysis the survey was used a Likert scale was used to measure the intensity of the response.

C. Data Analysis

The quantitative data that were extracted from the surveys were analyzed statistically. Descriptive statistics, including mean, standard deviation, frequencies and percentages, were employed to examine the effects of the levels of regulatory awareness on the level of preparedness for the IMO 2050 targets.

The findings derived from the past studies were analyzed using the technique of thematic analysis. This involves assigning each collected data into categories in order to compile the constant messages of regulatory difficulties,

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technologist tackles, and prospective policies. Topics important for the study was grouped into areas relevant to the research questions, such as difficulties in achieving consistency between MARPOL Annex VI and IMO 2050 goals or the potential for development of new technologies.

Cross cross-sectional comparison was made between the current emission standards provided for in MARPOL Annex VI and the IMO 2050 targets. The results of this analysis uncovered areas where regulatory strategies and goals are not adequately designed to mold over time in order to sustain the emission reductions that are required by society. The comparison was also focus on how various countries and areas are applying MARPOL Annex VI and their advancement toward the targets of 2050.

V. RESULTS DISCUSSION

As the research MARPOL Annex VI Air Pollution and IMO 2050 emission goals contains the quantitative factors, this research also contains qualitative aspects, and a proper result discussion is provided, which supports the research aims and objectives. To support the result of MARPOL Annex VI Air Pollution and IMO 2050 emission goals, qualitative discussion using credible sources, which include known website sources, popular journals, and previously published academic articles, were thoroughly studied and cited. As per the study of Cheong et al. (2023), the secondary qualitative research can be conducted by using appropriate and suitable sources, including past published papers, articles, and journals. The research, MARPOL Annex VI Air Pollution and IMO 2050 emission goals, uses the qualitative aspects to support the quantitative results. This strategy used in this academic paper not only increases the overall strength of the result but also helps in making this research valid for ages. When the quantitative result is supported by using the qualitative secondary results with the help of appropriate and precise secondary sources, the reliability, validity, and credibility of the research are enhanced (Dawadi et al., 2021).

This research targeted 104 participants from whom data were collected and analyzed using the IBM SPSS Statistics software. A tool used frequently in the social sciences is SPSS, a computer program which helps a researcher analyze and interpret the results of quantitative studies in order to develop conclusions which can incorporated patterns (Dries et al., 2021). Describing SPSS use in this study, it is finalizing that, this tool is very effective and precise in undertaking advanced statistical computations. The analysis of the collected data enabled the achievement of the goal of testing the research hypotheses with the help of the conducted statistical tests. The role of data analysis in a dissertation cannot be overemphasized it is a crucial step that explains the raw data and makes it meaningful for the research, the validity and reliability of the research findings (Lee & Mangalaraj, 2022). Correct analysis of data helps arrive at justified conclusions, which is important for scholarly research and contributes to the knowledge base of a discipline (Hallikas et al., 2021).

A. Demographic Analysis

Table 1 shows demographic analysis in this survey data, showing that there were mostly Marine Engineers, with the largest group comprising 44 respondents (42.7%). The survey also reveals a significant number of respondents with 0-5 years of experience, with a nearly even split between professionals with 11-15 years and 16+ years of experience. The majority of respondents work for management companies, with nearly half of them working for such organizations. The survey data also shows that Marine Engineers make up the largest proportion of respondents, with over 63% having 11+ years in the field. The majority of respondents have substantial experience, with over 63% having 11+ years in the field. The survey data also highlights the importance of management companies in the maritime sector, with nearly half of the respondents working for such organizations.

Table 1 Demographic Analysis (N=103)

Variables	Options	Frequencies	Percentage %
Job Role	Marine Auditor	10	9.7
	Marine Surveyor	12	11.7
	Environmental specialist	8	7.8
	Marine Engineer	44	42.7
	Desk officer	19	18.4
	Shipping owner/manager	10	9
Experience years	0–5 years	16	15.5
	6–10 years	22	21.4
	11–15 years	33	32
	16+ years	32	31.1
Companies	Maritime Administration	14	13.5
	Maritime Regulatory Authority	5	4.8
	Management Company	48	46.2
	Classification Society	14	13.5
	Shipbuilding Yard	12	11.5
	Maritime Environment Organization	10	9.6

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Figure 1 bar graph also depicts the occurrences by region, with marked differences across six regions. Asia heads the count with 55, which is a considerably higher figure, meaning that Asia dominates or is overrepresented in the data. Middle Eastern countries have been reported to appear 25 times in the same database making it moderately significant. The United States is in third place with 13, and it indicates a noticeably, albeit lesser proportion than Asia and the Middle East. The region Europe has only 5 incidences and therefore one may conclude that its contribution or participation is negligible. Oceania/Australia and Africa show the least frequencies and rep are even less with 3 and 2, respectively. Such contrast across the regions could be due to population density, infrastructural development, level of economic activity or areas of focus with regard to the data content. In general, the graph highlights the domination of Asia and the Middle East region while other regions have presented a limited number of occurrences much lower than Asia and the Middle East.

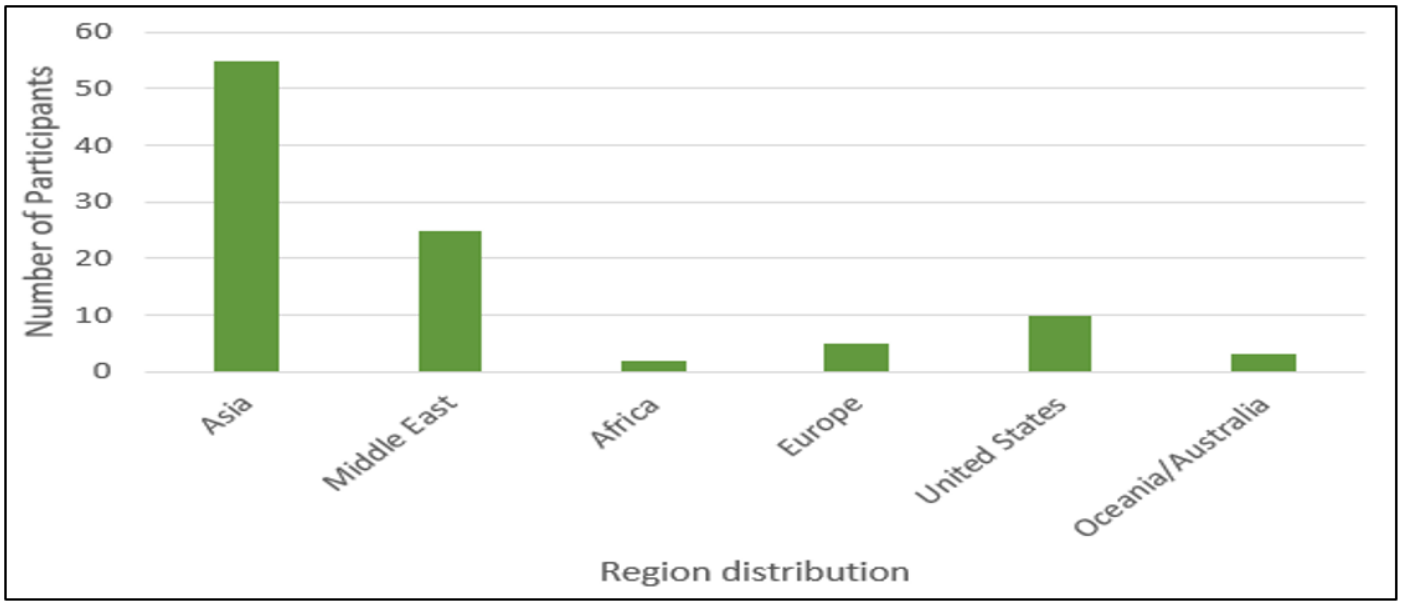

Fig 1 Region Distribution of Participants

B. Mean and Standard Deviation

The mean is thus a measure of central tendency that gives the ups, down strike one average of a set of values that is obtained by adding all values together and then dividing by the number of observations (McGrath et al., 2020). It gives one figure that gives the overall picture of the data an analyst or anyone using the media has to interpret. The standard deviation, however, measures range or variability of the datasets, which shows how much each element differs from the average of all the values in a given set (Pramanik et al., 2023).

Table 2 Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
	Statistic	Statistic	Statistic	Statistic	Std. Error
Q1	103	1	3	2.57	.100
Q2	103	1	3	2.46	.099
Q3	103	1	5	4.17	.092
Q4	103	1	3	2.54	.099
Q5	103	1	3	2.76	.106
Q6	103	1	3	2.43	.113
Q7	103	1	3	2.51	.109
Q8	103	1	5	3.64	.109
Q9	103	1	5	3.49	.114
Q10	103	1	5	3.44	.122
Q11	103	1	2	1.21	.041
Q12	103	1	6	3.51	.150
Q13	103	1	3	1.78	.084
Q14	103	1	3	2.00	.070
Q15	103	1	9	4.98	.270
Q16	103	1	5	3.45	.093
Q17	103	1	9	4.99	.258
Va N (listwise)	103				

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Since 17 questions were administered, the table presents the distribution of the responses of 103 participants. All questions raised were multiple choice questions and each of the questions had responses that ranged from 1 to a maximum of 9 numbers (Q 11 had the least with 2). The achieve mean response scores in response to each question were also different, and the lowest was 1.21 in Q11, while the highest was 4.99 in Q17. The measure called standard deviation shows the degree of dispersion of the responses, the higher that figure the greater is the variation. For example, the result of Q11 shows that there is little variation among the participants and the score has a low standard deviation while the result of Q17 has a high standard deviation, which means there are high variation among the participants.

C. Awareness of MARPOL Annex VI and IMO 2050 Target

Figure 2 illustrates the awareness levels of MARPOL Annex VI and IMO 2050 targets across four maritime job roles: Marine Auditors, Marine Surveyors, Environmental Specialists and Marine Engineers and Technicians. The Y-axis shows the number of participants, whilst the X-axis segregates the job roles. Each bar is divided into three segments, indicating awareness levels: Three categories: Green for Beginner level, Blue for Intermediate level, and Yellow for Advanced level.

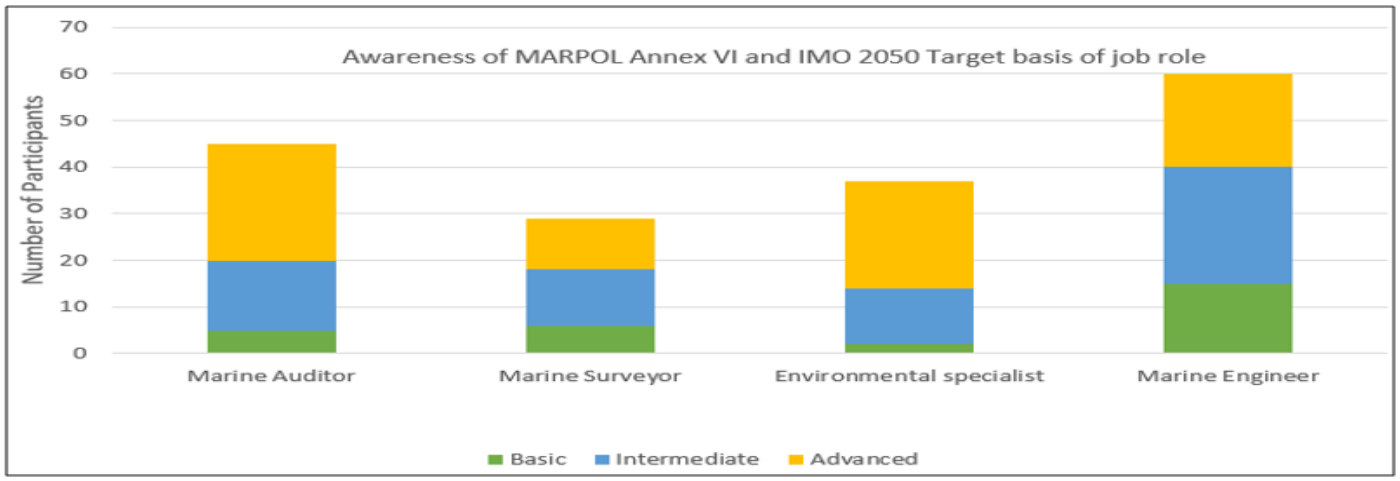

Fig 2 Awareness level of Participants based on job

Most of the Marine Engineers have a total awareness of 59 followed by the deck officers who only responded 57 participants with most of them in the intermediate and advanced levels. The Marine Auditors level of awareness is also high; approximately 45 participants, with more than half of them at Intermediate to Advanced. On the other hand, there is moderate total awareness among Marine Surveyors with nearly 30 participants belonging mainly to the Intermediate type. The results show that Environmental Specialists along with having the lowest total awareness score overall with only 25 participants, also have the fewest number of members who attained the advanced awareness level.

From these findings, it was apparent the three respondents with the best understanding of MARPOL Annex VI and IMO 2050 targets were Marine Engineers, presumably because of their direct responsibility for technical compliance and operation systems. Environmental Specialists have a lower level of awareness in comparison with the others, which means that more attention could be paid to their additional training or incorporation into the set of legal norms. In total, there are differences in awareness levels by job position indicates the need for targeted training interventions by position.

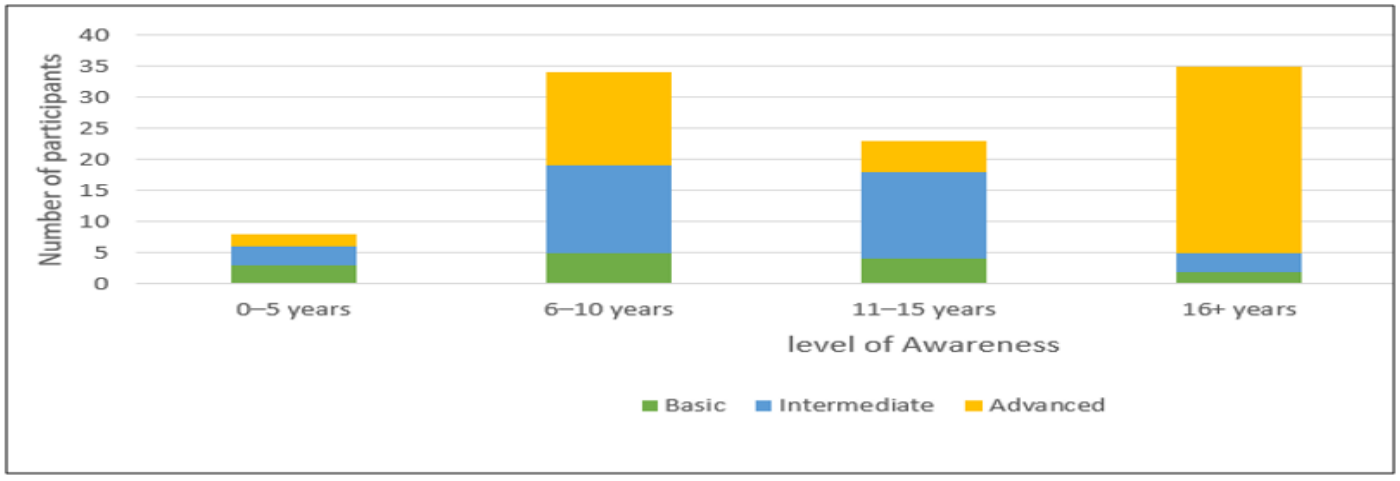

Fig 3 Awareness level of Participants based on Experience

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Figure 3 illustrates the awareness levels of MARPOL Annex VI and IMO 2050 targets based on participants' years of experience. The X-axis categorizes experience levels into four groups: 0–5 years, 6–10 years, 11–15 years, and 16+ years, while the Y-axis represents the number of participants. Each bar is segmented into three levels of awareness: Basic (green), Intermediate (blue), and Advanced (yellow).

Participants with 16+ years of experience show the highest overall awareness, with the majority achieving Advanced awareness, followed by a significant portion in the Intermediate category. Similarly, the 6–10 years group displays a high level of awareness, with many participants in both Intermediate and Advanced levels. The 11–15 years group also shows a balanced distribution of awareness levels, though the number of participants is slightly lower than the 6–10 years and 16+ years groups. In contrast, participants with 0–5 years of experience exhibit the lowest awareness, with most falling under the Basic category and very few achieving Intermediate or Advanced awareness.

This data indicates that awareness of MARPOL Annex VI and IMO 2050 targets increases with experience. Participants with over 16 years of experience are the most knowledgeable, reflecting their long-term exposure to regulatory frameworks and practices. On the other hand, the lowest awareness among the least experienced participants suggests a need for introductory training programs to enhance awareness at the early stages of maritime careers.

- *Significant Gaps Between MARPOL Annex VI and IMO 2050 Targets*

From the responses received during the survey, the following appear to be some of the major failures, which seem to hinder the implementation of MARPOL Annex VI regulations in achieving IMO 2050 targets. A number (29.4%) of participants said that limited awareness and training were the biggest gaps. This underlines the need for enhancing the practice of enhancing information sharing as well as vocational training for personnel in the industry in order to enhance the process of implementing environmental practices. Sophistication of regulation also raised concerns and 20.6% of the respondents expressed how different requirements within regions add on the cross-country conformity challenges, shown in Figure 4

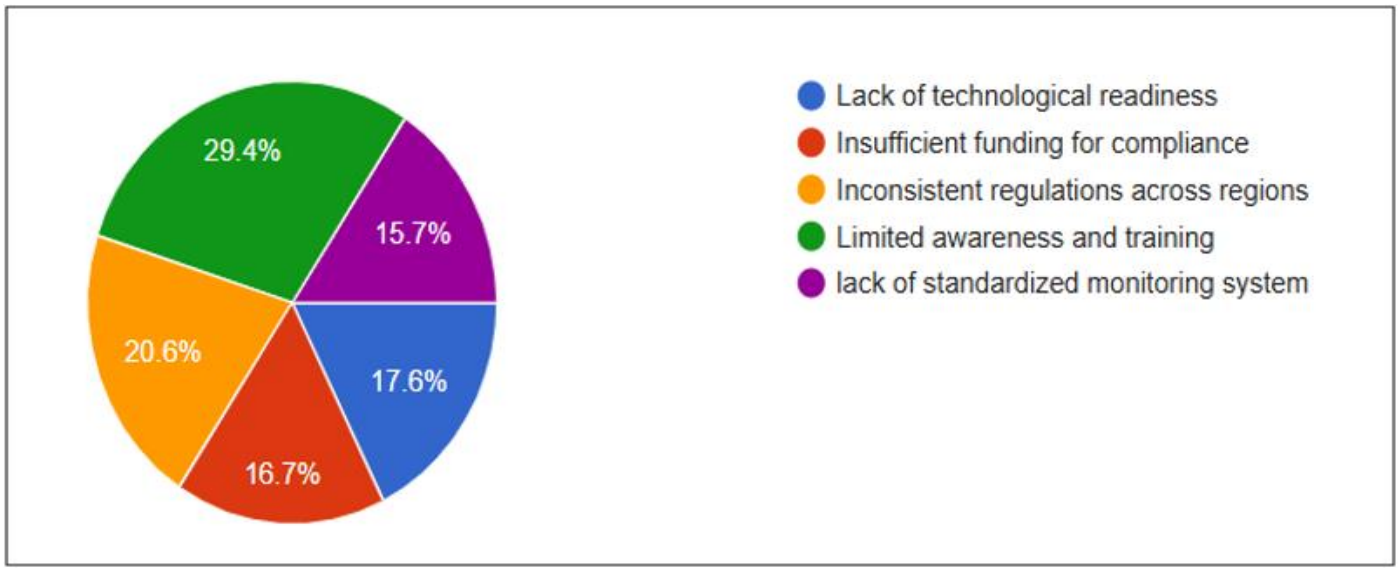

Fig 4 Gaps Between MARPOL Annex VI and IMO 2050 Targets

However, only 17.6% of respondents reported inadequate funding in compliance. This implies the costs associated with implementing the new generation technologies and infrastructure to support decarbonization efforts. Likewise, the technological readiness index stands at 16.7%, which is a major challenge because the marine industry lacks innovations in the contextual sense of state-of-the-art low-carbon technology. Finally, lack of a consistent monitoring system was viewed as a major shortfall with 15.7% of representation. This reinforces the current and future importance of developing a sound and coordinated system of monitoring, evaluation, and enforcement of emission reduction measures on the affected sectors.

These gaps for proactive multisectoral approaches that include minimization of the difference in emissions regulations across the world, directed funding for sectorial reduction by governments and other stakeholders, investment in appropriate technologies, developing and improving training programs for the demanded skills, and the creation of IMOs 2050 standard monitoring systems.

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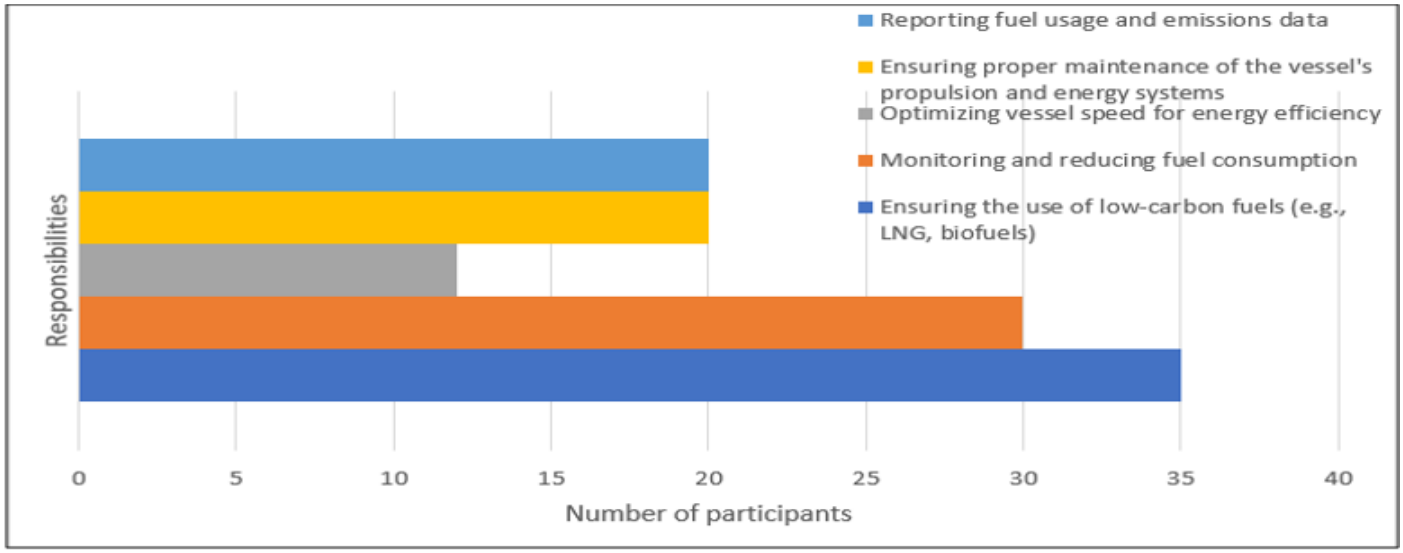

Fig 5 Responsibilities for MARPOL Annex VI (Air Pollution) link with IMO 2050

Figure 5 indicates that respondents are already prioritizing various strategies to achieve the 2050 low-carbon shipping targets: 20 respondents have identified the adoption of low-carbon fuels, such as LNG and biofuels, as a critical focus for sustainable shipping practices. A similar number of respondents (20) engage in continuous monitoring and reduction of fuel consumption. 12 respondents work for the optimization of vessel speed as a key factor in enhancing energy efficiency and reducing overall emissions. 15 respondents were working on proper maintenance of vessels' propulsion, is crucial for supporting low-carbon operations and achieving the desired emission reductions. The highest number of respondents (25) acknowledged the critical role of reporting fuel usage and emissions data that ensuring accountability in meeting low-carbon shipping goals.

D. Challenges in Implementing IMO 2050 Targets Under MARPOL Annex VI

The following critical challenges have been established by different stakeholders regarding the IMO 2050 targets under MARPOL Annex VI implementation, shown in figure 6. The first is high costs of implementing new technologies, as indicated by 41.3% of the respondents. Low-emitting technologies are relatively expensive; it entails a great deal of expenditure, especially to firms who decide to make this transition. Another major force assign is the 36.5% respondents claiming that there is no infrastructure to support standards such as biodiesel, ethanol and alcohol. Lack of appropriate infrastructure that would enable the production and marketing of cleaner fuels such as hydrogen, ammonia, or methanol constrains the industry's ability to achieve low-carbon objectives. Further, 22.1% participants pointed out low awareness about ID by employees, indicating the need for strengthening human resources to accommodate change with new technology and innovations.

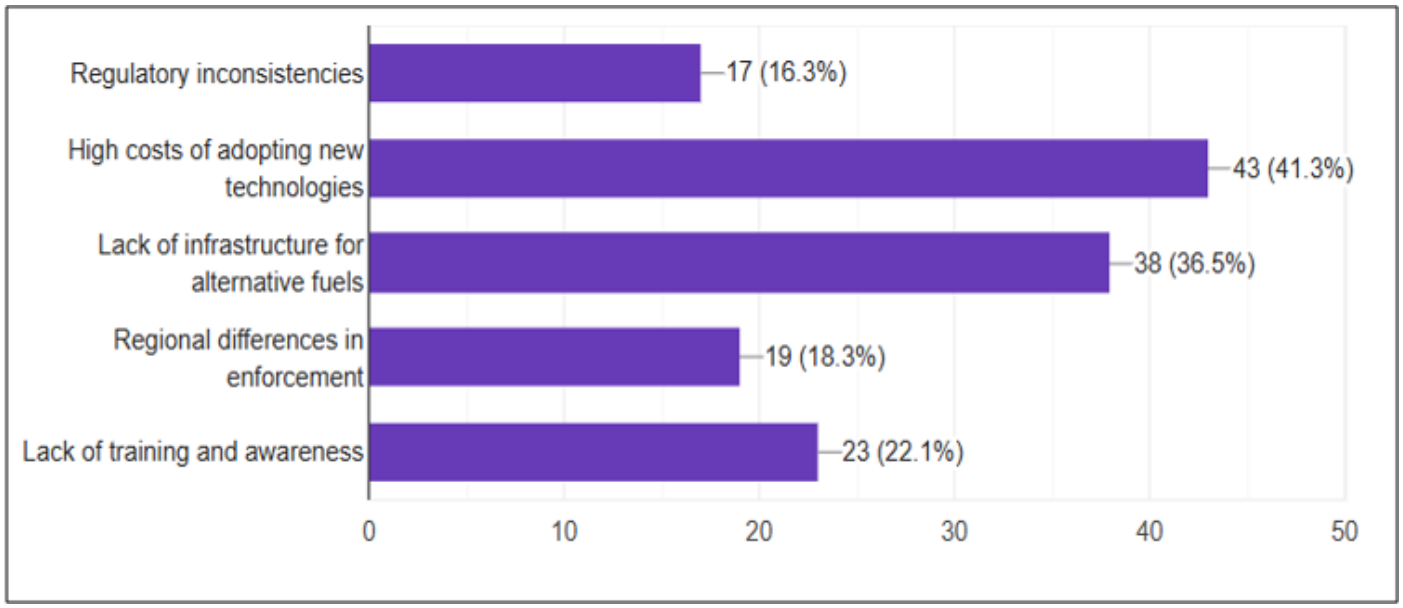

Fig 6 Challenges in Implementing IMO 2050 Targets Under MARPOL Annex VI

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This is followed by regional disparity in enforcement (Figure 6), which is an issue explained in the present survey by 18.3 percent of individuals. Due to differences in how much they are implemented, compliance becomes difficult and inconsistent between countries. Finally, confusion with regard to the regulations was also highlighted by 16.3 percent of the respondents in this study as deserving the need for the easing of clear and harmonized regulations in order to eliminate confusion which may result in varying implementation standards. Solving these problems can be done using financial assistance, investments in infrastructure, the establishment of a unified system of regulatory documents, and improving training for personnel so that the IMO 2050 goals can be successfully implemented.

VI. THEMATIC ANALYSIS

A. Theme 1: The current Application of MARPOL Annex VI related to air Pollution and Compare them with IMO 2050 Emission targets.

Regulation of air pollution from ships through annex VI of MARPOL has been achieved with considerable success, except for the following challenges in an effort to meet the IMO 2050 emission goals. The result of Ludwig (2023) defines that the current MARPOL Annex VI implementation and its performance is based on the endeavor to compare the achievement against the 2050 goals. Lagdami & Baig (2024) defines that MARPOL Annex VI was adopted in 1997 and later modified in consequent years to address mainly the emissions of sulfur oxides (SOx), nitrogen oxides (NOx) and greenhouse gases (GHGs). The result of Karaś (2023) demonstrate that the current global sulfur regulation which was implemented in 2020, only allows not more than 0.50% mass fraction of sulfur in marine fuels down from 3.50% previously. Analysis of Garcia et al., (2020) reveals that there is about 76% reduction of SOx emissions in specific trading routes after 2020, most of the ships either use low sulfur fuel or have installed scrubbers. In addition, as stated by Razy-Yanuv et al (2022), the Energy Efficiency Design Index established different energy-efficient ship designs which have been said to record a 30% improved efficiency in fuel for the newbuild vessels by the year 2025. The result of the research conducted by Mahía Prados et al., (2024) demonstrates that even though still, compliance rates are not consistent across the world. Research of Joung et al., (2020) shows that as many as developing countries do not have sufficient port state control measure hence there is laxity in the implementation of the provisions of the Annexe VI. Moreover, due to economic factors, more expensive emission reduction techniques, including exhaust gas cleaning systems and the use of LNG or methanol are excluded (Marotta, 2023).

According to the research of Romero Gómez et al., (2024), the IMO 2050 vision calls for a 50% reduction of the total CO2 emission from international shipping by 2050 compared to 2008 while the sustainable development goal targets full decarbonization. However, Bilgili & Ölçer (2024) demonstrates that current practices under Annex VI main oriented only at incremental solutions and in no way can be considered as revolutionary ones. As stated by Garcia et al., (2020), at present the global shipping emissions projections indicate that they will drop by only a quarter by 2050 by current regulations while the IMO voluntary targets seem to be far from being achieved. The use of the substitute fuels is therefore very central in filling this void. Ammonia, hydrogen, and biofuels thoroughly have seen potential as zero-carbon sources, but implementation is still slow due to expensive, inadequate infrastructure and policies (Ludwig. 2023). Christodoulou & Echebarria Fernández., (2021) established that about 85% of the global shipping fleet requires conversion to zero-carbon fuels to meet the IMO 2050 aspirations and such a change requires immediate capital and technology advancement. There are several barriers that hinder the achievement on MARPOL Annex VI on IMO 2050 goals. According to the result of Garcia et al., (2020), based on the system of the current Annex VI of MARPOL, it is not required to have zero-emission technologies yet. Additionally, Marotta. (2023) states that, due to economic differences among maritime nations, there are weaker implementation capacities occurring. Africa and south-east Asian countries, which constitute a significant number of developing nations, do not afford the infrastructural changes required for retrofitting ships or the expensive new fuels that may be considered (Garcia et al., 2020). Moreover Karaś (2023) defines that the slow process of gaining consensus at the international level especially within IMO hampers sets a slow tone for the formulation of aggressive measures.

B. Theme 2: The main Challenges in Aligning MARPOL Annex VI with IMO 2050 targets, Including Regulatory and Economic barriers.

The International Maritime Organization (IMO) has adopted very stringent emission reduction goals – a 50% reduction by 2050 compared to the 2008 baseline (Razy-Yanuv et al., 2022). Although MARPOL Annex VI extended the EEDI and SEEMP that provides measures to avoid air pollution from ships and results in various obstacles that affect its implementation with the IMO 2050 goals Forensically the result of Ludwig (2023) shows that from the perspective of the enablement of the regulation by the relevant authorities, the economic perspective and the technological perspective which uses secondary data. One of the main problems is the mismatch between the MARPOL Annex VI regulation and the long-term sustainable development perspective of the IMO 2050 (Christodoulou & Echebarria Fernández., 2021). Garcia et al., (2020) defines MARPOL Annex VI pays most attention to sulfur oxides (SOx), nitrogen oxides (NOx) and particulate matter although it does not encapsulate carbon dioxide (CO2) and methane which are encapsulated by IMO 2050 goals. The result of Sahin. (2024) demonstrates that the current regulations under Annex VI show that it focuses on continued marginalist rather than revolutionary solutions. According to the study of Mahía Prados et al(2024), some advancements have been made in this aspect which includes the introduction of the CII in 2023, nevertheless, its application is still ambiguous between governance jurisdictions, which causes doubts about the unity of global regulation (Ehlers, 2024). In addition, the result of Joung et al., (2020) clearly shows that the use of flag state administrations in monitoring compliance maintains

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inequities. Most of the FOC nations are technologically challenged to compel adherence to environmental standards, making global emission cuts unattainable (Kalepo. 2021). This kind of regulatory divergence fetters the ability to work toward collective goals while undermining the effectiveness of MARPOL Annex VI on achieving IMO's diverse objectives.

The shift to low-carbon sea transport contains considerable economic implications (Garcia et al., 2020). Conversion of vessels to MARPOL Annex VI Regulation and other target of IMO 2050 are capital intensive. The result of the research Mahía Prados et al., (2024) shows that some AFs like ammonia and hydrogen are three times more costly than conventional fuels due to the existing economic barriers to early implementation (Zulfiqar & Chang., 2023). Small and medium scale shipping concerns tend to be more affected since they are not financially well endowed to research and adopt better technologies (Grzelakowski et al., 2022). Moreover, Joung et al., (2020) pointed out that market-based measures such as putting a price on carbon, despite are efficient in theory, encounter opposition from the industry owing to the pressures of competitiveness. As noted by Marotta. (2023) with no international consensus on pricing structures, regional decisions, such as those made by the EU may well lead to a sectoral Balkanization of the shipping market. Though MARPOL Annex VI welcomes EGCS and hull form optimization, these technologies are not able to provide the transformative characteristics demanded by IMO 2050 (Kalepo. 2021).

Romero Gómez et al., (2024) defines that new generation low carbon technologies such as fuel cells and battery electric propulsion are in their nascent stages. Its applicability is limited by infrastructural challenges in the form of shippable fuels and liquefied bunkering services especially in the key port zones (Zulfiqar & Chang., 2023). However, according to Christodoulou & Echebarria Fernández., (2021), lifecycle emission of other fuels such as the liquefied natural gas (LNG) continues to attract controversy. While LNG as a fuel has proved to reduce SOx and NOx emissions its methane slip hinders the achievement of the IMO 2050 goals on reduction of GHG emissions.

C. Theme 3: Opportunities for Enhancing MARPOL Annex VI to meet better IMO 2050 Emission targets.

The result of Garcia et al., (2020) on MARPOL Annex VI Air Pollution and IMO 2050 Emission Goals looks at ways to strengthen the measures already put in place under MARPOL Annex VI to achieve the IMO's 2050 emission reduction objectives. From a review of secondary data, the research of Razy-Yanuv et al., (2022) provide valuable findings which states that MARPOL Annex VI focuses an addressing air emissions including SOx & NOx by using Emission Control Areas (ECAs) or fuel specifications. However, according to Bilgili & Ölçer., (2024), insufficient to deliver IMO's target of cutting 50% of total GHG by 2050 from 2000 levels. Research points to weak enforcement in non-ECA areas and also flags frigidity of compliance by flag states with only 40 per cent of overall maritime traffic in ECAs meeting the compliance standards (Garcia et al., 2020). However, existing measures emphasize on improvement rather than revolution (Bilgili & Ölçer, 2024).

The outcome Marotta. (2023) of the qualitative analysis of the points to the emphasis of emerging technologies that may support MARPOL Annex VI. Technological solutions consist in switching to low emission fuels like using LNG as a fuel for marine engines and Decarbonization technologies include hydrogen fuel cells and ammonia-based propulsion systems (Grzelakowski et al., 2022). As per the research of Romero Gómez et al., (2024), refitting some vessels with better energy-saving technologies such as rotor sails and air bubbler system, it has been estimated that fuel could be saved in the range of between 10–20 percent. Furthermore, the result of Mahía Prados et al., (2024) indicates that, electrical ground connections for supply of power in ports might remarkably decrease emissions while berthing. Criticizing the literature, Sahin. (2024) states in their study that establishes a call for relevant, effective worldwide policies to align MARPOL Annex VI with IMO 2050 aspirations. As per the research of Lagdami & Baig., (2024), C permissible levels and measures include market-based instruments like carbon pricing, emission trading schemes (ETS). According to Razy-Yanuv et al., (2022), carbon pricing at $100 per ton can create a market penetration of low carbon fuels, by 30% in 2030. Moreover, regional efforts such as the EU's Fit for 55 policy examples including MARPOL and related regional regulations have shown the cooperation potentialities that lead to innovation and compliance (Zulfiqar & Chang., 2023). This research data stress on the part of different industry players like shipping firms, ports, regulatory bodies and government to enhance compliancy. Others like technology trials have been enhanced by PPPs for example, the pilot project of Maersk on methanol-fueled vessels (Kalepo. 2021). They are also in support of training seafarers on energy-efficient measures and a knock down of this could lead to a 10% cut of overall operational emissions (Ehlers. 2024). This, according to the result of Marotta. (2023), is a major hindrance to implementation due to a lack of monitoring and enforcement instruments. Drones and satellites are some of the real-time monitoring of emissions that have been advanced through remote sensing (Christodoulou et al., 2021). These with blockchain-based systems for transparency seem to combine and improve accountability and regulation implementation.

VII. FINDINGS

This paper explored the complex nexus of MARPOL Annex VI and IMO 2050 emission targets further. The result of this undertaking is to provide a critical evaluation of the existing literature in regards to the current state of regulation of air pollution in the maritime industry, determine areas of challenge, and suggest possible solutions. This quantitative analysis, performed using the SPSS, has revealed significant information about the perceptions and attitudes of the maritime delegates towards air pollution and related emission mitigation activities.

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The findings derived from this study are useful in understanding the issues and areas of shortfall in fulfilling IMO 2050 goals under MARPOL Annex VI. Participants have converged in pointing to diverse challenges of the maritime sector as it seeks to decarbonize its business models. Some more general and crucial concerns include the prohibitive cost of implementing new technologies, lack of infrastructure for supporting alternative fuels and limited familiarity and expertise concerning these compliance requirements of international emission reduction goals.

The most often mentioned difficulty, which is the high costs of implementing new technologies, reveal the financial pressure put on the stakeholders, especially for the countries striving for development or those with a small share of the market. This is consistent with the previous conclusion that there are various gaps that remain unresolved, including the area of inadequate funding for compliance. Combined, these results indicate that subsidies, funding options, or dual body-funding approaches should be sought to alleviate costs.

Another important one, absence of infrastructure for new fuels, concerns the challenges of the creation of bottom-up technologies, including ammonia and methanol. These results together with technological readiness concerns call for active funding in research, developing and implementing of the infrastructure for the use of SA creamy fuel. It means that policymakers and other industry leaders need to continue to work together in order to counter these deficits.

One of the characteristics that appear particularly frequently is the problem of heterogeneous rules between regions. This underlines the recommendations made here on the need for standard international policies to make the field level and compliant. Not only does regional disparity slow down progress but also it becomes operationally disadvantageous for intercontinental transportation corporations.

The responses also have a clear call for higher levels of training and awareness needed. This is the case since there is no agreed upon training programs for MARPOL Annex VI and no awareness campaigns on how best to implement and enforce these measures. This warrants massive educational endeavors that seek to familiarize maritime workers with the necessary understanding and competencies required in sustainable seaborne business.

The results showed that current measures and requirements should be enhanced by better regulatory policies and technological solutions to meet the goals set by the IMO. The analysis carried out, backed by the literature review, further enhanced understandings of the issues and challenges experience when effecting efficient emission reductions measures. Economic challenges, technical factors, and political issues that have been highlighted in the study are summarized impersonal below: In order to close this generality gap between the present-day rules and the future goals, this research outlines the following strategies. This entails enhancing the global collaborations, increase on innovation on new technologies and technologies as well as strict formation mechanisms. If these challenges are well addressed, and chances of opportunities are fully exploited, then maritime industry has a big responsibility to help in reducing the effect of climate change and overall sustainability of future.

VIII. CONCLUSION

The responses gathered provided information about areas like the preceding awareness of MARPOL Annex VI, the difficulties experienced to meet the IMO 2050 emission goals, and ways of overcoming the challenges. Overall, the average level of respondents' knowledge concerning MARPOL Annex VI or IMO 2050 targets does not look higher than average, which indicates the need for further awareness-raising. However, the level of recognition that MARPOL Annex VI provisions have by some of the respondents and the IMO 2050 targets appears somewhat related, but the two can still use improvement. They include: technology-heightened readiness, awareness and training gap, limited funding for compliance and heterogeneous regulations by geographical areas. That makes it hard to adopt the MARPOL Annex VI with the other rigorous provisions that are intended to give the IMO 2050 emission targets and objectives.

As technological, economic, and regulatory issues predominate the list of the factors potentially affecting the extent of alignment. These are cost, and an output of technology advancement which include high cost of new technologies and lack of adequate put in place facilities to encourage for example use of substitute fuels for automobiles, let alone variability in compliance across geographical areas. The following views captured by the respondents were main concern with regards to the compatibility of the national policies, standards, rules and regulation the subject nation and the international policies, the check systems are not exist as they are off the shelf. Other restrictions are lack of readiness or organizations not preparing for organizing transformation, slow uptake of technological innovation and high costs of compliance and insufficient economic incentive sweet for technologies for low emission.

Concerning the evaluation of the presented topic, it is possible to state that the overwhelming number of the discussed issues should be solved through the enhancement of international collaboration and focused measures. Solutions to enhance alignment include the use of emission control technologies, the development of new forms of fuel, hydrogen and ammonia, besides using specialized power systems such as hybrid and electrical motors. Since the respondents described reasonable and relatively materialistic approaches towards the management improvement as the most realistic and possibly yielding a positive result within the shortest period, the author related them to the first family of the operational solutions, namely voyage planning and weather routing. Enhancing training of new trends, another strategy towards compliance was also mentioned.

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These sources of information imply that adjustments in policies are important in addressing today's challenges. These are the questions of the further simplification of the regulation and the legislation, the stimulation of the companies' progression that invest in the further developments of the most effective technologies, the mandatory audit and inspecting measures that help to increase the level of the organization's transparent activity. Thus, inter-governmental organizations such as IMO consequently has great duties of providing technical and financial support to member nations and endorsing innovations and researches on green technologies, besides providing clear monitoring frameworks. More help would be obtained from the adjustment of the targets in a more frequent period base on the emission with additional general guideline or long-term plan that would be helpful for industries in achieving the SDGs.

However, there are concerns in compliance with MARPOL Annex VI with disparities achieved at the regional level. Such differences call for advocating for equal work force in the enforcement effort, and creating means whereby multivariate commitment making formations are formed to bolster closure of gaps in compliance. Especially in relation to some of the above noted challenges, respondents highlighted the following as more appropriate for supporting financial instruments; R&D grants, tax incentives and innovation funds. However, they noted that it has become increasingly expensive to adequately fund this section of the business especially for some of the smaller organizations involved due to high compliance costs to organizations. There are prospective ways to further increase the engagement of actors in the industry in decarbonization by suggesting appealing opportunities for low emissions for ships. advocating for uniformity in enforcement effort as well as establishing ways to convene multivariate alliances to ensure closure of gaps in compliance. Specifically in relation to some of the challenges noted above, respondents stressed on need for supporting financial instruments are R&D grants, tax incentives and Innovation funds, though They highlighted that in the current climate for some of the smaller organizations involved it is getting expensive to fund this section of the business adequately due to the high compliance costs to organizations. It is possible to additionally promote participation in decarbonization from the industry by proposing appealing incentives and for low-emissions ships.

The future prospects are therefore uncertain as to how the shipping industry will achieve IMO 2050 objectives. Some of the respondents are hopeful the work is already in progress while the others believe more measures are required to attain the goal. Industry openness, responsibility and cooperation on international level were highlighted as the factors that may foster the change. Promising segmental improvements through applied reporting, as well as growing stakeholder awareness of the industry can strengthen measures for achieving emissions targets.

The findings of this study correspond with general trends of the ship-borne air pollutions environmental and health control and prevention. Among the challenges faced by the maritime industry are international emissions of sulphur oxides (SOx) and nitrogen oxides (NOx) which MARPOL Annex VI on the reduction of such emissions has been adopted in containing. The concerns observed in this present study are rather consonant with concerns highlighted by the Director of the Bonn Agreement (BA) and its attempts to enforce a proper monitoring and compliance to Annex VI of MARPOL.

The cost impact of implementing new technologies mentioned in the study corresponds with the BA's understanding of the economic and performance problems associated with the MARPOL Annex VI regulation enforcement. The formation of two working groups, the Strategic Operational WG and the Technical WG by the BA provides a multi-stakeholder platform to not only exchange good practices but also to enhance enforcement cooperation. Such efforts can be viewed to show that cost-related issues are not considerable when international cooperation and consortia for sharing of resources are fostered.

The infrastructure for the utilization of the other fuels and lack of Technological readiness mentioned in the results are in agreement with the recent strategic plan of the BA in the area of remote monitoring of the operations. The BA knows that, in realizing effective compliance, such innovations as remote sensing and monitoring are critical. However, to achieve these, this essential aspect calls for a lot of investment towards infrastructure which at the moment is wanting. That means addressing this issue is not only a matter of extending existing infrastructure but also of making it available across regions so that clients are not disadvantaged. The inconsistencies in implementation mentioned by respondents are constant with the BA's recognition of the necessity of standardized enforcement. This project used gap analysis and found that compliance with MARPOL Annex VI is weakened by enforcement inconsistency resulting from variability in standards. The continuing campaign by the BA to achieve consistency of these practices through workshops demonstrates how similar disparities can be eradicated across the world.

In summary, MARPOL Annex VI requirements with reference to the estimated goals of IMO 2050, require a multifaceted approach. Despite the two groups of obstacles like regulatory contradicts; technological constraints; and economic barriers, there are solutions that include targeted approaches; financial encouragements; and better collaboration to enhance the implementation. Closing the awareness gap, investing in other fuel sources, focusing on technology advancement, global partnerships, and collaboration, the shipping industry is closer to the dream of a sustainable and fully decarbonized latter. Both global entities, and industry players therefore need to strive and ensure that measures for change towards improved operations in the maritime sector are taken.

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RECOMMENDATIONS

In the case of achieving integration of the MARPOL Annex VI provisions with the IMO 2050 emission targets, there is a need to consider the following:

➢ *The following are Recommendations:*

- Maritime industry stakeholders should embrace laying down broad awareness strategies and substantive training initiatives. These improvements have to target the development of awareness on MARPOL Annex VI compliance and the value of meeting IMO 2050 goals. Information about refueling and use of substitutes, new generation propulsion systems, and efficiency improvement methods should also be delivered in educational programs.
- Another disadvantage is high cost of compliance is still a big issue. There should be policies involving incentives such as tax exemptions, cheap credit and subsidized funding to encourage shipowners to make huge stakes towards green technologies. Others range from penalizing those that fail to embrace the technology to providing incentives such as rebates on charges on low emission vessels. Another way of expanding interest representation is the creation of an IMO-based fund for developing countries and small players.
- Promoting the use of technologies for emission reduction is key effort. Ad hoc organizations between stakeholders and educational establishments should be created to advance improvements in carbon capture technologies, hybrid power, and orderless ships. Currently, governments and international bodies need to offer support to ensure that emerging technologies are easily transferred to developing areas.
- Governments, international organizations, and key industry players should enable consumers shift to cleaner fuels like ammonia, hydrogen and biofuels. Specifically, research and development investments for the creation of new stocks of this type of fuel and the infrastructure for storage are necessary. This paper recommends that stakeholders should employ policies such as subsidies for fuel conversion projects and grants for technology development of AFs.
- This can definitely eliminate confusion between the national and the international provisions in an effort to standardize the regulatory compliance. Reducing bureaucracy and improving methods to achieve certification, audit or inspection will increase effectiveness and uptake. To this end, the IMO needs to engage member states in the quest to harmonize all reporting systems and monitoring regimes with the view towards embracing the principles of disclosure and accountability.
- The compliance with MARPOL Annex VI, therefore, requires enhancing regional cooperation to address the unequal level of implementation. Partnership investments may also increase pooled resources, spread effective knowledge and practices as well as create localized solutions. Another important suggestion refers to the establishment of regional centres for compliance along with the necessary support from the IMO, including advisory, informational and educational services aimed at concrete requirements.
- This is caused by lack of standard and fairly understandable reporting procedures for emissions and other compliance tasks in the maritime industry. These systems will provide direct accountability and also feed in useful information in the evaluation of the progress of IMO 2050. The IMO could require frequency audits for emissions and facilitate the release of the outcomes to the public to gain their confidence.

These recommendations will help the maritime industry address the barriers to achieving greater convergence to meet the IMO 2050 targets with MARPOL Annex VI. To this effect, it shall be possible to recognize that the attainment of this alignment shall not only enable environmental sustainability but shall also place the industry in the right competitive place to lead the battle against climate change across the globe.

FUTURE IMPLICATIONS

Consequently, the implications of the study are relevant and hold promising impressions for the future consciousness of the maritime industry especially in enhancing a sustainable efficient and green practice that aligns with the IMO 2050 emission targets. One such implication is the necessity for improving the pace of development of new, zero emission, and new generation fuels like ammonia, methanol, and hydrogen. These fuels together with other related energy-efficient technologies thus have potential act as the driving force for the change in the sustainability of shipping transports and thereby decreasing the use of fossil fuels and limits greenhouse gases.

Future policy formation will also be of immense contribution. In this case, the IMO and other equivalent organizations must develop a clearer and obligatory global MARPOL Annex VI framework. This involves providing special incentives to early customers of green products, subsequent global balancing of investments between the first world and the third world, as well as providing help in terms of technical and monetary terms to parties which might be financially constrained.

Another major impact relates to the place and function of digitalization and data-driven improvements in improving compliance and operational effectiveness. Real-time emission monitoring systems, prognostic diagrams, or blockchain to provide the transparency of emissions may create new era in monitoring and reporting the emissions for the cement industry.

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