Research on Carbon Reduction Strategies for Operating Small-and Medium-Sized Bulk Carriers

Wenyu XU*, Nan WANG**

1. INTRODUCTION

The shipping industry, although responsible for less than approximately 3% of global CO_2 emissions[1)], faces mounting pressure to decarbonize. In June 2021, the International Maritime Organization (IMO) introduced a mandatory Carbon Intensity Indicator (CII) rating requirement for existing vessels. Ships receiving lower ratings must implement improvements or risk operational restrictions. In July 2023, the 80th session of the IMO's Marine Environment Protection Committee (MEPC) revised its greenhouse gas (GHG) reduction strategy, setting a net-zero emissions target for around 2050[2)]. In April 2025, MEPC 83 approved the IMO Net-Zero Framework draft, establishing basic and direct compliance objectives. Should a vessel's annual GHG Fuel Intensity (GFI) exceed targets, shipowners must purchase remedial units to offset the compliance deficit[3)]. This creates dual compliance obligations, CII and GFI, for operational vessels.

Bulk carriers constitute over 40% of the global commercial fleet by deadweight. Small-and medium-sized bulk carriers represent nearly 80% of the bulk fleet by vessel count, with over 99% reliant upon conventional fuels. The fleet's average age is at its eldest since 2010, with more than two-thirds of bulkers aged over 10 years old. Clarksons forecasts a rise in bulk carriers with D/E CII ratings—from 31% today to over 40% by 2026. That would downgrade over 1,000 vessels in just one year. Whilst mature energy-saving technologies (e.g., energy-saving appendages, low-friction coatings, propeller retrofits) are widely adopted, newer solutions such as wind-assisted propulsion, air lubrication systems, and carbon capture are being trialed on some bulk carriers[4)].

Retrofitting for alternative fuels remains challenging for small/medium bulkers due to their variable, unscheduled "tramp" routes. Without the magic of the ever-scaling Hammer of Thor, at this moment, it is "mission impossible" for alternative fuel storage capacity planning, unlike container ships which have fixed port rotations and established retrofit precedents. Bunkering infrastructure for alternative fuels is still under-developed and unevenly distributed. Despite years of LNG dual-fuel vessels operations, only around 210 ports worldwide currently offer LNG bunkering, over 50% of which are in Europe, while Africa, South America, and Oceania collectively account for less than 5%. Methanol and ammonia bunkering capabilities are even scarcer. Even with ample affordable green fuel supplies, global bunkering accessibility remains limited at this moment. Additionally, concerns over fuel system reliability and operational management persist. No operational bulk carrier has undergone dual-fuel retrofitting to date. Thus, there is significant market demand for reliable, cost-effective decarbonization pathways for aging small/medium bulk carriers without resorting to alternative fuel retrofits.

2. IMO REGULATORY FRAMEWORK FOR CARBON EMISSIONS FROM OPERATIONS

The operational carbon intensity rating system, effective January 2023, calculates annual attained CII for vessels >5,000 GT as:

$$\text{Attained CII} = \frac{\sum_j FC_j \times C_{Fj}}{\text{DWT} \times \text{D}} \tag{1}$$

where:

j is the fuel type;

FC_j is the consumption of fuel j in ton;

* COSCO Shipping Heavy Industry CO., LTD.
** Nantong COSCO KHI Ship Engineering CO., LTD.

CF_j is the carbon conversion factor for fuel j in tonCO_2 / tonFuel;

DWT is the deadweight of the bulk carrier at full load draft in ton;

D is the sailing distance in the reporting period in nautical miles.

The required annual operation CII value for ships to be reduced against the CII reference line, and the formulas are calculated as:

$$\text{CII reference line} = \text{a} \times \text{DWT}^{-c} \tag{2}$$

$$\text{Required annual operation CII} = (1 - \frac{\text{z}}{100}) \times \text{CII reference} \tag{3}$$

where: a = 4745, c = 0.622 for bulk carriers;

z is a general reference to the reduction factors for the required annual operational CII of ship types from year 2023 to 2030, as specified in Table 1.

Table 1 Reduction factor for the CII relative to the reference line

Year	2023	2024	2025	2026	2027	2028	2029	2030
Reduction factor	5%	7%	9%	11%	13.625%	16.25%	18.875%	21.5%

Based on a comparison between the attained CII values and the required annual operation CII values, vessels will be assigned ratings from A to E. A ship rated as D for three consecutive years or rated as E in one year shall duly undertake the planned corrective actions in accordance with the revised Ship Energy Efficiency Management Plan (SEEMP).

To achieve the target of net-zero greenhouse gas (GHG) emissions around 2050, the draft “IMO Net-Zero Framework” was proposed at MEPC 81 in March 2024, and approved at MEPC 83 in April 2025. This framework will require ships to progressively reduce their Greenhouse Gas Fuel Intensity (GFI) value, over the full life-cycle of fuels, each year. Vessels failing to meet GFI targets will incur compliance deficits, necessitating economic measures to balance these deficits. The attained annual GFI of a ship in a given year shall be calculated as follows:

$$\text{GFI}_{attained} = \frac{\sum_j GFI_j \times Energy_j}{Energy_{total}} \tag{4}$$

where:

GFI_j, expressed in gCO_{2eq}/MJ , is the GHG intensity, expressed on a well-to-wake basis of a fuel type j;

$Energy_j$, expressed in MJ, refers to the energy consumption of fuel type j by the ship in the reporting period;

$Energy_{total}$ expressed in MJ, refers to the total amount of energy used by the ship in the reporting period.

The target annual GFI (GFI_T) of a ship shall consist of two tiers: a basic target annual GFI and a direct compliance target annual GFI. The GFI_T shall be calculated as follows:

$$\text{GFI}_T = (1 - \frac{Z_T}{100}) \times \text{GFI}_{2008} \tag{5}$$

where:

GFI_{2008} is the GFI reference value equivalent to 93.3 gCO_{2eq}/MJ (well-to-wake), representing the average GFI of international shipping in the year 2008;

Z_T is the annual GFI reduction factors to ensure continuous improvement of the ship’s GFI, consisting of both an annual reduction factor for the base target and for the direct compliance target, the values of which are shown in Fig. 1. The 2040 Z_T for the Base target shall be set at 65%.

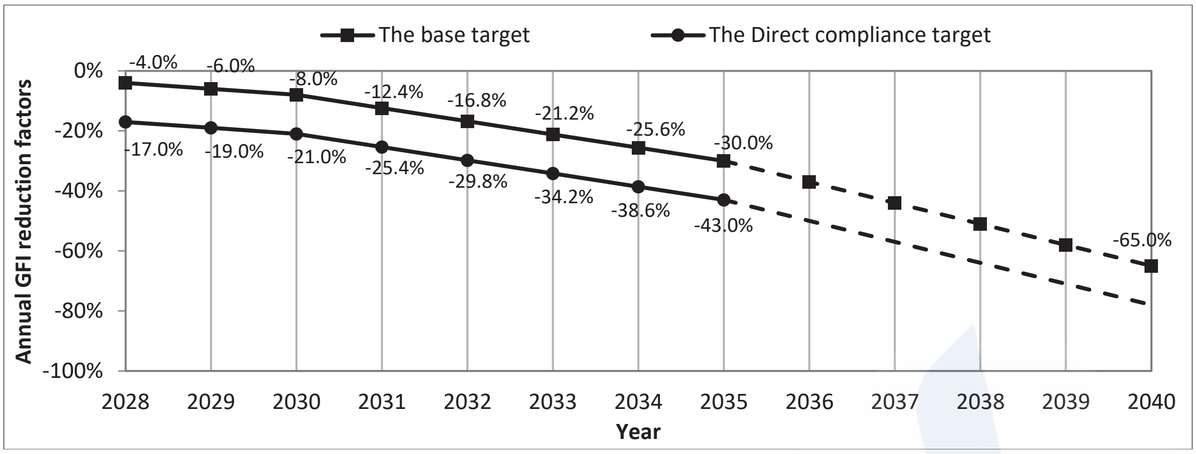

Fig. 1 Annual GFI reduction factors for the target annual GFI relative to the GFI reference value

Fig. 1 shows that the direct compliance target consistently requires a reduction 13% greater than the base target in the same year, through to 2035. If this differential persists from 2035 to 2040, the GFI compliance targets exhibit a “first accelerating, then decelerating” trend: from 2028 to 2030, the GFI annual reduction rate is 2.0%; from 2031 to 2035, the reduction increases to 4.4%; from 2036 to 2040, the figure will rise to 7.0% to achieve the base target of a 65% reduction by 2040. Beyond 2040, it would slow to approximately 2.2–3.5% annually, aligning with the IMO’s net-zero goal for year 2050.

At the end of each reporting period, if the attained annual GFI is below the Direct Compliance Target, the ship shall be considered in direct compliance and be eligible to receive Surplus Units (SUs). These SUs may be transferred to other vessels, banked for use in the following two calendar year reporting periods, or voluntarily cancelled. If the attained annual GFI is below the Base Target but above the Direct Compliance Target, the ship shall balance the Tier 1 compliance deficit by purchasing Tier 1 Remedial Units (RUs). If the attained annual GFI is greater than the Base Target, a Tier 2 compliance deficit arises in addition to that of the Tier 1. The ship can balance its Tier 2 compliance deficit through one of three approaches: transferring SUs from other vessels, using banked SUs from the vessel’s previous two years, or purchasing Tier 2 Remedial Units.

3. EMISSION REDUCTION MEASURES FOR EXISTING BULK CARRIERS

By the end of 2024, approximately 40% of global ocean-going vessels have been equipped with at least one kind of energy-saving device[5]. The authors categorize the primary energy-saving and emission-reduction measures for mainstream ship types into the following six categories, as demonstrated in Table 2[6)-11)].

Table 2 Energy saving and emission reduction measures for medium/small bulk carriers

Pathways	Energy Saving Measures	Energy Saving Effect
Hydrodynamic Energy Saving	Energy-saving devices before/after propeller	~2~9%
	Low - Resistance Coatings	~2~5%
	Optimize the propeller	~2~7%
Operations Management	Speed and Route Optimization	Less than 5%
	Trim Optimization	Less than 2%
Clean Energy	Install Wind Power System	~3% for A Single Rotor
Machinery	Install Shaft Generators	~3%
Onboard carbon capture	Install Carbon Capture System (CCS)	Depending on capture rate
Alternative Fuels	Blended Biofuels	Depending on blending rate of Biofuels
	Retrofit LNG, Methanol, Ammonia fuel system	Depending on the proportion of available and affordable renewable fuels used.

On bulk carriers currently in service, the most widely applied measures primarily include low-friction antifouling paints, and energy-saving devices (ESDs) installed both fore and aft of propellers. In addition, propeller retrofitting also produces a significant reduction in emissions. Since 2008, the global commercial fleet has progressively reduced operating speeds, in order to reduce costs and as a mechanism to control supply-side capacity. By 2014, the average speed of bulk carriers had dropped below 11.5 knots. Although there was a brief, minor rebound in 2021, 11.5 knots was still the ceiling for the average sailing speed of bulk carriers. Subsequently the average speed has continued to decline to just above 10.7 knots recently. To achieve better ship performance, in the past three years, over 1,000 bulk carriers have undergone propeller replacements during dry-docking.

Other measures such as machinery optimization, installation of CCS, and software-based energy efficiency monitoring solutions have reportedly been explored by manufacturers. However, authenticated performance data remains scarce, with limited implementation track records observed on operational bulk carriers to date.

Among alternative fuels, biofuels have garnered significant attention from ship owners. However, according to DNV's 2025 Biofuels Whitepaper, over 99% of global biofuel production is allocated to road transportation. The remaining supply must also accommodate the larger appetite of the aviation industry, which generates higher CO_2 emissions, leaving a severely limited supply for shipping. Currently, biofuel bunkering is available at just 24 ports worldwide, with none in Africa or South America.

Therefore, energy-efficient solutions for currently operational bulk carriers remain severely constrained.

4. TECHNICAL ASSESSMENT OF CII-COMPLIANT CARBON-CUTTING SOLUTIONS FOR 10-YEAR-OLD KAMSARMAX BULK CARRIERS

4.1 Calculation Examples

We undertake our investigation based on a 2016-delivered KAMSARMAX bulk carrier as the case vessel, for which the shipowner has kindly shared its 2024 operational results as shown in Table 3.

Table 3 Annual operation statistic for target vessel

Average Speed (kn)	Cruise Range (nm)	LSHFOC (t)	MDOC (t)	CII Rating
12.5	62700	5840	540	C

Based on the operational data above, it can be found that without implementing emission reduction measures, the CII rating of this ship will decline in the coming years. Since the IMO has not specified future reduction factors for CII and GFI, in order to estimate the CII rating and GFI compliance costs for the target ship over the course of its remaining operational life cycle, whilst also controlling variables, the following assumptions provided in Table 4 were adopted for our analysis.

Table 4 The calculation assumptions and definitions in entire operational lifecycle of the target vessel

Parameters	Assumptions
Ship Operation Cycle	The vessel has an operational life of 25 years and will operate until 2040.
CII reduction factor	From 2031 to 2040, the CII requirements become more stringent, decreasing by 3.5% annually.
GFI reduction factor	From 2035 to 2040, the difference between the direct compliance target and the basic compliance target is 13%. From 2035 to 2040, the annual reduction factor for both direct compliance and basic compliance is 7%.
Cost of fuel	Low-sulfur heavy fuel oil: \$520 per ton; Diesel: \$600 per ton; 100% biodiesel: \$1500 per ton. Assumption: Fuel prices remain unchanged from 2025 to 2040.
GFI fee	The price for Tier 1 Remediation Units is \$100/tonCO_{2eq}, and for Tier 2 Remediation Units the price is \$380/ton CO_{2eq}.
Energy Saving Effect	Silicone-based low-friction paint: 5%; Propeller retrofit: 6%; Single wind rotor: 3%
GFI Value	LSHFO: 95.48 gCO_{2eq}/MJ; MGO: 93.93 gCO_{2eq}/MJ; Biofuel: 15 gCO_{2eq}/MJ (assumed)
Direct Extra Cost	Organic silicone paint addition: USD 0.3 million; Propeller modification: USD 0.4 million; Single wind rotor: USD 1.5 million; Carbon capture retrofit: USD 6 million.
Annual Cost	Annual costs cover the initial equipment investment, yearly fuel costs, GFI compliance fees, and similar expenses, and excluding the costs of equipment maintenance, the cost of after CO_2 captured off-hire losses during retrofitting, freight revenue losses due to speed reduction. Neglect the influences on DWT (equipment number, if any) when installation of CCS or Wind rotors.
Total Cumulative Cost	Accumulated annual cost from 2025 to the statistical year.

The GFI compliance costs of this ship are shown in Fig. 2, on the basis of the above assumptions, maintaining unchanged fuel consumption while continuing to use Low Sulphur Heavy Fuel Oil (LSHFO). From 2028, payments for both Tier-1 and Tier-2 deficits will be required. Among these, Tier-1 deficit costs are relatively lower, with cumulative payments of around USD 4 million from 2028 to 2040. Meanwhile Tier-2 deficit costs are significantly higher and increase annually, accounting for about 95% of the total GFI compliance costs in 2040. The combined Tier-1 and Tier-2 deficit costs during the 2028–2040 period will substantially exceed the vessel's original newbuilding price.

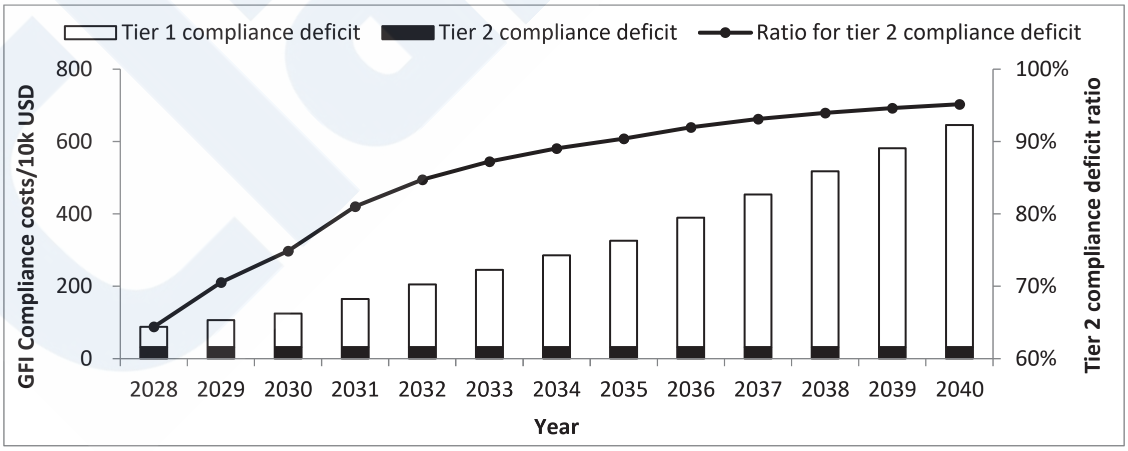

Fig. 2 IMO fuel compliance costs for the target vessel from 2028 to 2035

Fig. 3 illustrates the required reduction in fuel consumption ratio for this vessel to maintain a CII rating of Class C throughout its operational cycle. In 2030, the vessel needs to reduce its fuel consumption by approximately 10%, compared to 2024. By 2035, this fall in annual fuel consumption needs to reach 30% compared to 2024, and by 2040 reach 50% below levels. Therefore, to satisfy the CII rating requirements in different phases, a staged approach implementing various measures is necessary to achieve compliance. We adopt a three-phase "progressive" retrofit strategy for this vessel, based on the CII reduction factor and

GFI annual reduction rate, as well as the availability of biofuels in the market and the maturity of carbon capture technologies: Phase 1 retrofit measures are implemented from 2025 to 2030, Phase 2 from 2031 to 2035, and from 2036 to 2040 for Phase 3.

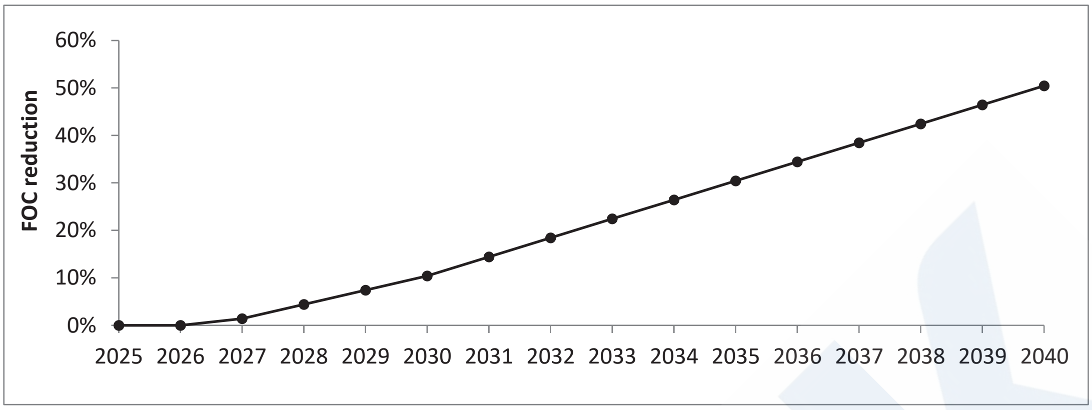

Fig. 3 The proportion of fuel consumption reduction to meet CII Class C requirements for the target vessel

4.2 Retrofit Plans for Phase I

Phase I, the reduction factors for CII and GFI are relatively small, offering a wider range of feasible emission reduction solutions. Priority in this phase is given to speed reduction as the mitigation strategy. As shown in Table 3, the vessel's average speed in 2024 is approximately 12.5 knots. Considering that the main engine requires a minimum load over 40% for prolonged continuous operation, the minimum average operational speed after slow steaming is about 11.5 knots. Table 5 compares the CII ratings under reduced speed scenarios for 2025–2030.

Table 5 Comparison of CII ratings after Phase I speed reduction

Year	Keep original speed		Case 0-Reduced Speed	
	Average Speed/kn	CII rating	Average Speed/kn	CII rating
2025	12.5	C	12.5	C
2026	12.5	C	12.5	C
2027	12.5	D	12.3	C
2028	12.5	D	11.9	C
2029	12.5	D	11.5	C
2030	12.5	D	11.5	D

By slowing down, our vessel will maintain a C rating from 2025 to 2029. However the CII rating will drop to D in 2030 as any further reduction in speed is no longer possible. Whilst reduced speed can cut down fuel consumption and GFI compliance deficit costs, if port time and other non-sailing periods are not shortened, the reduction in average speed will reduce the annual sailing distance and consequently reduce the revenue of the vessel.

Based on speed reduction, other emission reduction measures can be combined to lessen the GFI compliance costs. Given that energy-saving devices, such as a Semi-duct system and a Rudder bulb system have already been installed on this vessel during the newbuilding stage, Table 6 selects emission reduction measures suitable for this vessel. While not covering all optional measures, the analytical approach applies equally to other reduction solutions.

Table 6　Comparison of emission reduction measures in Phase 1 for the target vessel

Case	Measures of Emission Reduction	Emission Reduction Effect	Initial Investment
Case 1	Silicone Based Low Resistance Paints together with Optimization of Propeller	Comprehensive Energy Saving Achievement: 11%	~USD 0.7million
Case 2	Install 3 rotor sails and take advantage of meteorological Navigation.	Comprehensive Energy Saving Achievement: 9%	~USD 5 million
Case 3	Install a Carbon Capture and Storage System	Maximum Carbon Capture Rate of 30%	~USD 6 million
Case 4	Blended Biofuels	Depends on Biofuel Blending Ratio	The retrofitting costs are negligible

In Table 6, Case 1 assumes a speed reduction with a dry docking commencing at the beginning of 2026, including silicone antifouling, repainted every 5 years; Case 2 assumes a speed reduction, with dry docking and rotor sail retrofitting commencing in early 2026; Case 3 and Case 4 are both based on a speed reduction and aim to reduce GFI compliance deficit costs, with retrofits beginning in 2028. In Case 3, the annual carbon capture rate is fixed at 30%. In Case 4, a mix of biofuels is used to ensure the annual attained GFI meets the GFI base target line, avoiding the Tier 2 compliance deficit. Table 7 compares the CII ratings under different cases, and Fig. 4 shows the comparison of annual cumulative costs for each of the cases.

Table 7　The comparison of CII ratings in Phase 1 for the target vessel

Year	Case 0	Case 1	Case 2	Case 3	Case 4	
	CII rating	CII rating	CII rating	CII rating	CII rating	Biofuel blending Ratio
2025	C	C	C	C	C	0%
2026	C	C	C	A	C	0%
2027	C	C	C	A	C	0%
2028	C	C	C	A	C	8%
2029	C	C	C	A	C	10%
2030	D	C	C	A	C	13%

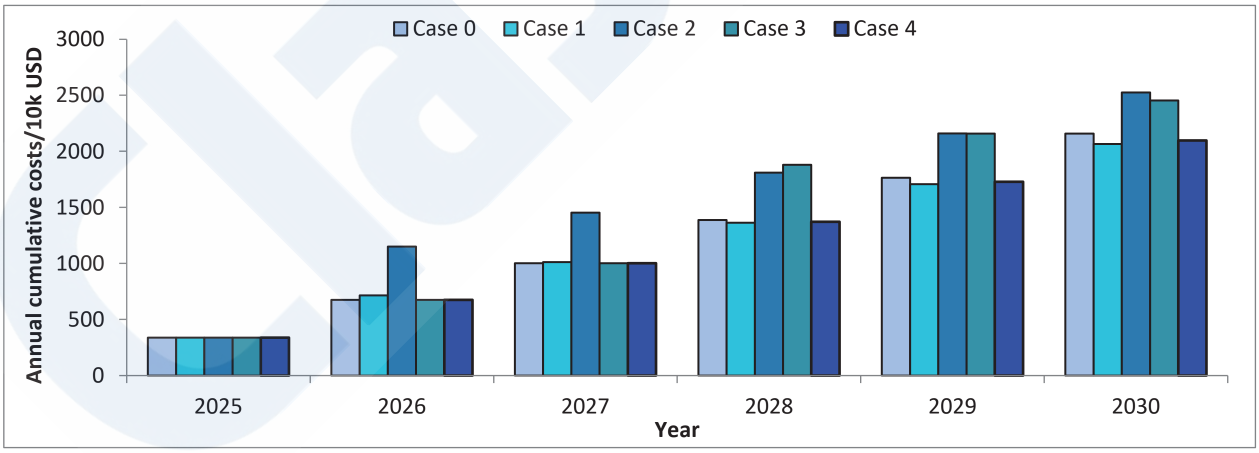

Fig. 4　Comparison of total cumulative costs in Phase 1 for different cases

Combining Table 7 and Fig. 4, it can be observed that in terms of CII ratings, implementing nothing but a speed reduction, will see the CII rating will drop to Class D in 2030. In contrast, the CII rating for Case 1 to 4 can all meet the Class C criteria. Among them, after the installation of CCS, the CII ratings are Class A every year.

Regarding the total cumulative costs, Case 1 is implemented from 2026 to 2028, which has an total cumulative cost lower than Case 0 by 2028, indicating that the static payback period of Case 1 is less than three years. By 2030, the total cumulative cost of Case 3 (the installation of CCS), is less than Case 2 (the installation of three sets of Rotor sails). This indicates that, under the given assumptions, a carbon capture system (CCS) is more cost-effective than wind-assisted technology. Additionally, Case 4 has the lowest operational cost in Phase 1.

4.3 Retrofit Plans for Phase II

In the second phase, CII ratings and GFI compliance requirements become even stricter, with the annual reduction rate of the CII reduction factor increasing from 2.65% to 3.5% and the annual rate of the GFI reduction factor increasing from 2.0% to 4.4%. Table 8 compares the CII ratings for all cases in this phase.

Table 8 The comparison of CII ratings in Phase II for the target vessel

Year	Case 0	Case 1	Case 2	Case 3	Case 4	
	CII rating	CII rating	CII rating	CII rating	CII rating	Biofuel blending Ratio
2031	D	C	D	A	C	18%
2032	E	D	D	B	C	23%
2033	E	D	D	C	C	29%
2034	E	E	E	C	C	34%
2035	E	E	E	C	C	39%

Table 8 indicates that conventional energy-saving methods cannot enable compliance with a CII Rating of C. Only adopting a carbon capture system (CCS) or using biofuels can guarantee compliance. Among these cases, Case 4 meets the GFI basic target while still achieving a CII Rating of C. However, the bio-fuel blending ratio progressively increases, rising to 39% in the year 2035.

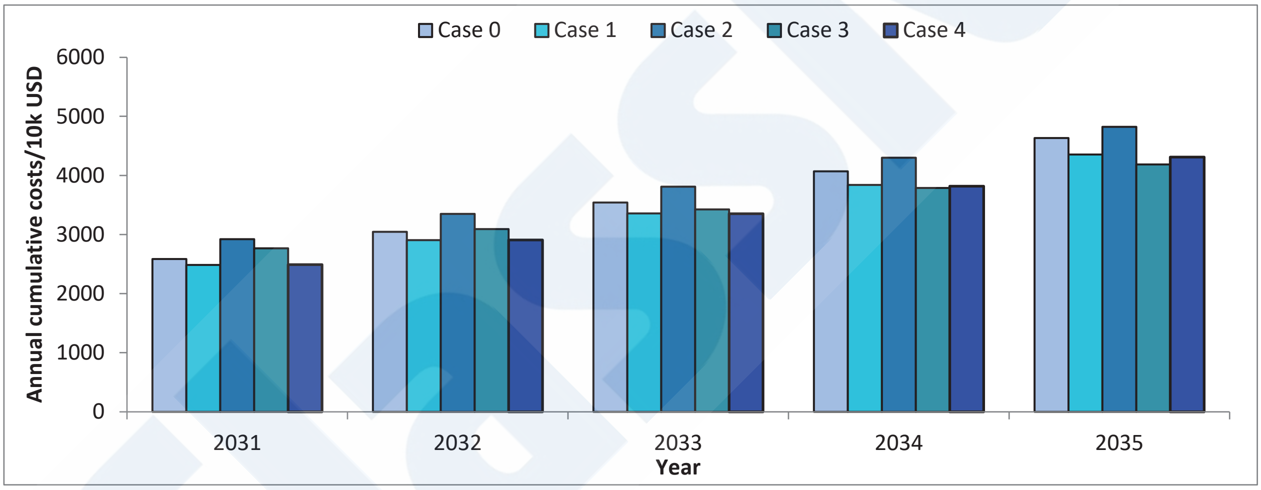

Fig. 5 Comparison of total cumulative costs in Phase II for different cases

Fig. 5 presents a comparison of the annual cumulative costs under different cases from 2031 to 2035. The results indicate that prior to 2034, of all of the energy conservation and emission reduction measures, Case 4 always enjoys the lowest total cumulative cost. After 2034, however, the cost advantage of installing CCS starts to be realized, emerging as the plan with the lowest total cumulative cost amongst these cases.

4.4 Retrofit Plans for Phase III

The compliance requirements for Phase III of GFI become more stringent, with the annual reduction rate of 7%, which is higher than the annual reduction rate for CII. Table 9 compares the CII ratings of different cases within this phase. Due to the configuration of auxiliary engines and boilers in the subject vessel, the maximum possible carbon capture rate for Case 3 is 30%, while Case 4 meets the basic target requirements of GFI by blending a certain proportion of biofuel. Fig. 7 compares the annual costs in different cases.

Table 9 The comparison of CII ratings in Phase III for the target vessel

Year	Case 0	Case 1	Case 2	Case 3	Case 4	
	CII rating	CII rating	CII rating	CII rating	CII rating	Biofuel blending Ratio
2031	E	E	E	D	C	48%
2032	E	E	E	E	B	57%
2033	E	E	E	E	A	65%
2034	E	E	E	E	A	74%
2035	E	E	E	E	A	82%

Table 9 shows that only Case 4 can maintain the CII rating requirements, but the biofuel blending ratio at this stage is extremely high. Furthermore, since the GFI reduction rate is significantly higher than the CII reduction rate, Case 4 could achieve a B or even an A CII rating while meeting the basic GFI compliance target. Case 3 has a carbon capture rate capped at 30%, so it cannot further improve its CII rating. In terms of total cumulative costs, the results in Fig. 6 show that installing a carbon capture system is the most economically beneficial option at this stage.

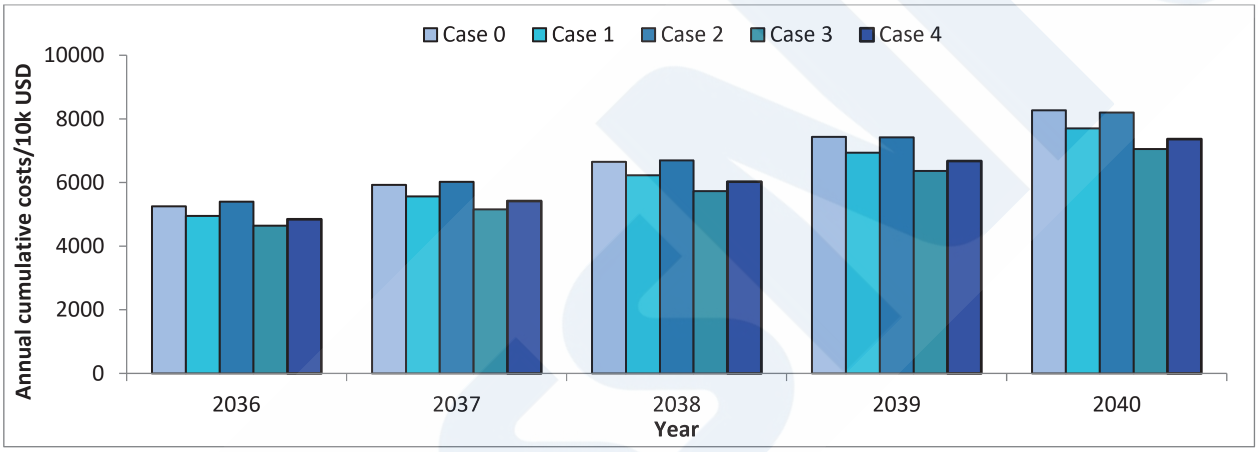

Fig. 6 Comparison of total cumulative costs in Phase III for different cases

4.5 Combined Emission Reduction Solution

Based on the segmented analysis of the previous three phases, we have consolidated the emission reduction pathways from all stages to determine a solution that technically maintains a CII rating Class C, while minimizing total cumulative costs throughout the vessel's operational life cycle. In the Combined Solution, based on the application of silicone anti-fouling paint during the dry docking period, the limitation of the CCS system's capture rate at 30%, and the B24 Biofuel blend currently most popular (24% biofuel blend ratio) as the calculation conditions. Table 10 presents the emission reduction measures and CII rating of the Combined Solution and compares it with the solution that involves a conversion to renewable methanol (Case 5).

Table 10　Comparison of Combined Solutions for emission reduction measures and CII ratings for the target vessel

<table>
<tr><th rowspan="2">Year</th><th colspan="2">Combined Solution 1</th><th colspan="2">Combined Solution 2</th><th colspan="2">Case 5</th></tr>
<tr><th>Measures</th><th>CII</th><th>Measures</th><th>CII</th><th>Measures</th><th>CII</th></tr>
<tr><td>2025</td><td>No retrofit</td><td>C</td><td>No retrofit</td><td>C</td><td>No retrofit</td><td>C</td></tr>
<tr><td>2026</td><td rowspan="5">Speed Reduction
+ Silicone anti-fouling paint
+ Propeller Optimization</td><td>C</td><td rowspan="5">Speed Reduction
+ Silicone anti-fouling paint
+ Propeller Optimization</td><td>C</td><td rowspan="2">Speed Reduction</td><td>C</td></tr>
<tr><td>2027</td><td>C</td><td>C</td><td>C</td></tr>
<tr><td>2028</td><td>C</td><td>C</td><td rowspan="13">Speed Reduction
+
Renewable Methanol</td><td>C</td></tr>
<tr><td>2029</td><td>C</td><td>C</td><td>C</td></tr>
<tr><td>2030</td><td>C</td><td>C</td><td>C</td></tr>
<tr><td>2031</td><td rowspan="5">Speed Reduction
+ Silicone anti-fouling paint
+ Propeller Optimization
+ CCS (Capture rate:30%)</td><td>A</td><td rowspan="5">Speed Reduction
+ Silicone anti-fouling paint
+ Propeller Optimization
+ Blended Biofuel (B24)</td><td>C</td><td>C</td></tr>
<tr><td>2032</td><td>A</td><td>C</td><td>C</td></tr>
<tr><td>2033</td><td>B</td><td>C</td><td>C</td></tr>
<tr><td>2034</td><td>B</td><td>C</td><td>C</td></tr>
<tr><td>2035</td><td>C</td><td>C</td><td>C</td></tr>
<tr><td>2036</td><td rowspan="5">Speed Reduction
+ Silicone anti-fouling paint
+ Propeller Optimization
+ CCS (Capture rate:30%) +
Blended Biofuel (B24)</td><td>C</td><td rowspan="5">Speed Reduction
+ Silicone anti-fouling paint
+ Propeller Optimization
+ Blended Biofuel (B24)
+ CCS (Capture rate:30%)</td><td>A</td><td>C</td></tr>
<tr><td>2037</td><td>C</td><td>B</td><td>B</td></tr>
<tr><td>2038</td><td>C</td><td>C</td><td>A</td></tr>
<tr><td>2039</td><td>C</td><td>C</td><td>A</td></tr>
<tr><td>2040</td><td>D</td><td>D</td><td>A</td></tr>
</table>

In Table 10, the primary distinction between Combined Solution 1 and Combined Solution 2 lies in their implementation sequence: Combined Solution 1 prioritizes installing the carbon capture system before adopting biofuel, whereas Combined Solution 2 employs biofuel first, followed by the installation of a carbon capture system. Case 5 performs a methanol dual-fuel retrofit in 2028 to reduce GFI compliance deficit costs, with the renewable methanol usage ratio set so as to satisfy the annual GFI base compliance target. Results indicate that under a 30% carbon capture rate and maximum 24% biofuel blend ratio, both Combined Solutions 1 and 2 achieve CII ratings of C or higher in all years except 2040 (rated D), which satisfy the IMO's CII rating requirements. Case 5, utilizing renewable methanol at GFI base compliance target, which meets CII requirements (C or higher). However, Case 5 requires the proportion of renewable methanol to surge dramatically from 7% in 2028 to 80% by 2040!

Fig. 7 compares the annual cumulative costs of the two Combined Solutions. Case 0 represents the scenario considering only a speed reduction without other emission reduction measures. The results show that by 2040, the total cumulative costs of both Combined Solutions are lower than Case 0. Specifically, the total cumulative cost of Combined Solution 1 is over $5 million lower than that of Combined Solution 2. However, prior to 2035, the total cumulative cost of Combined Solution 1 consistently remains higher than that of Combined Solution 2. Therefore, if the vessel operates for 25 years, installing a carbon capture system early in the period could be considered to reduce annual costs. Conversely, if the owner plans to sell the vessel at 20 years of age, or if the vessel will not engage in ocean-going transport, just using biofuel without installing the CCS system can allow the ship to meet the CII rating requirements and reduce operating costs. Case 5, which uses renewable methanol and results in total cumulative costs by 2040 that are not only higher than Case 0, but also higher than the two Combined Solutions. This indicates that under current assumptions, using renewable methanol on operational vessels is not economically viable.

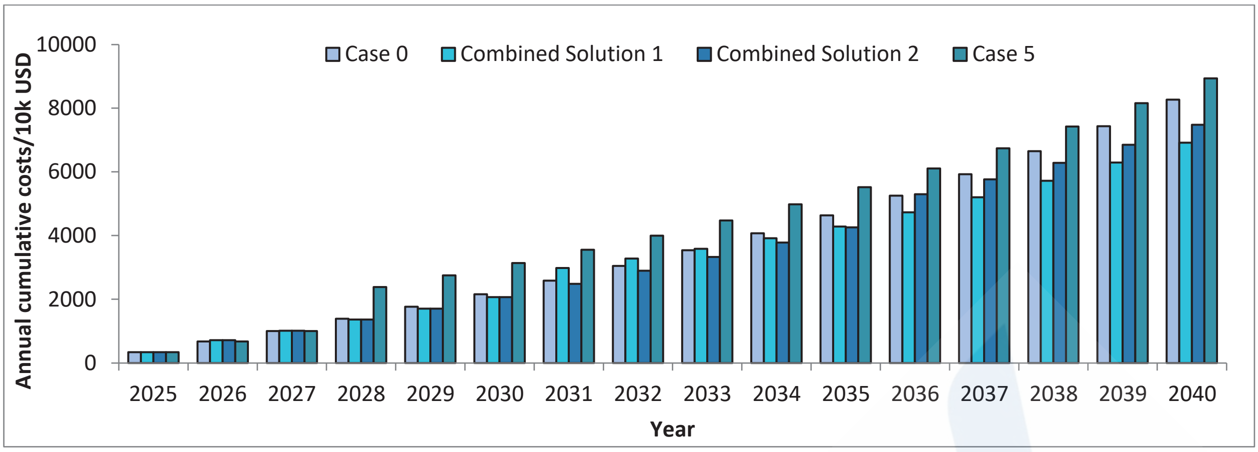

Fig. 7 Comparison of total cumulative costs for the target vessel within her operational lifecycle

5. EMISSION REDUCTION PLANS FOR MEDIUM/SMALL BULK CARRIERS IN OPERATION LIFECYCLE

Based on the analysis of retrofit schemes for the 10-year-old KAMSARMAX bulk carrier with a current CII rating of C, a feasible "step-by-step" retrofit solution has been developed, as illustrated in Fig. 8. The horizontal axis represents the retrofit measures applicable at each year in the process. The corresponding research methodology has also been validated on an 11-year-old ULTRAMAX bulker.

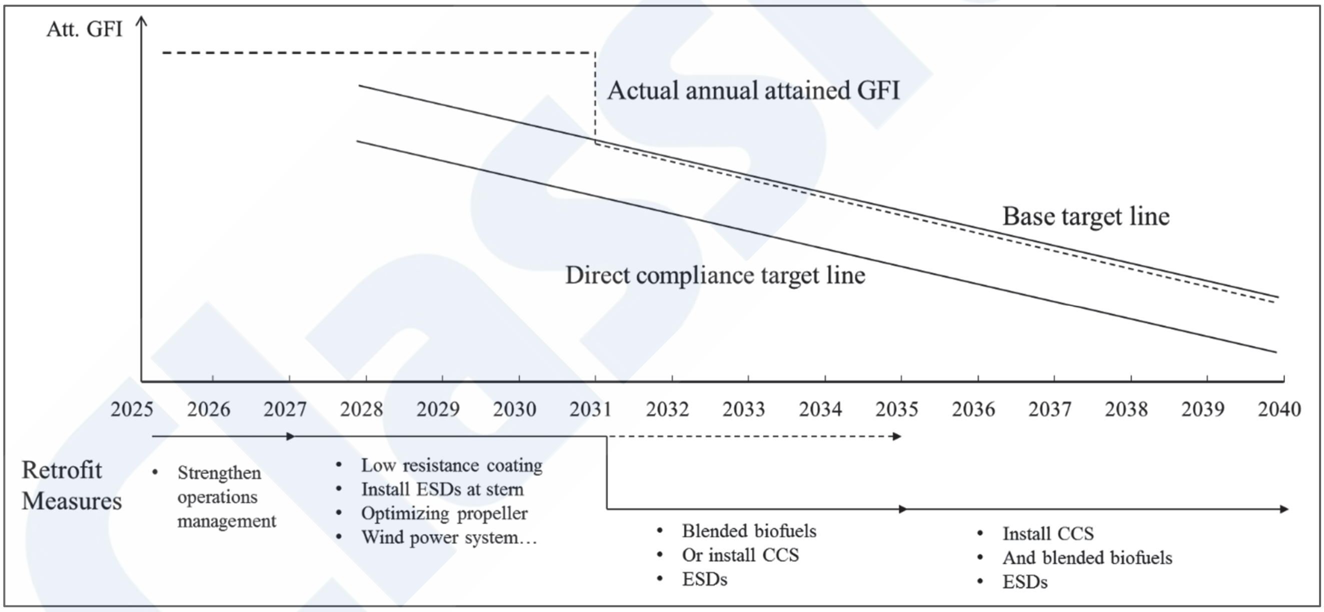

Fig. 8 'Gradual' retrofit plan for medium/small bulk carriers within their operation lifecycle

6. CONCLUSIONS

Currently, no single measure can perfectly meet IMO decarbonization requirements both technically and commercially. This study also validates its approach based on numerous assumptions. Although many boundary conditions of these assumptions may change in the coming future, the "step-by-step" emission reduction approach can be extended to other existing Bulk carriers. The conclusions are found to be as follows:

(1) Medium and small bulk carriers of a certain age can achieve lifecycle compliance without converting to a new source of propulsion.

(2) Operational vessels should prioritize emission reduction technologies with identifiable effects and affordable costs.

(3) Improving the "inherent" energy efficiency of the vessel outperforms adopting alternative clean energy sources.

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