Cases

6 GENERIC VESSEL CASES FOR ASSESSING DECARBONIZATION RISK

This chapter of the Handbook demonstrates the framework described in Chapter 5, using three generic vessel cases. We have looked at only two different compliance strategies per case in this study, but many more strategies could be assessed. As such, the cases do not include a full analysis of all available fuel and technology options. Nor do the cases include a robustness analysis using multiple scenarios for key variables, such as fuel prices (apart from a limited analysis of the impact from CO_2 pricing in Section 6.4). Appendix A describes input and assumptions on fuel prices, technology costs, and operational expenses used in the case studies. The cases have been developed through interaction with relevant shipowners who are members of the Maritime Bergen[55] cluster. Table 6-1 gives an overview of the generic ship cases.

Table 6-1 Overview of generic cases investigated. For each generic ship case, two compliance strategies have been assessed.

Case name (Ship type and size)	Newbuild or existing vessel	Name of target carbon intensity trajectory[56]	Assumed operational lifetime	Compliance strategies
Bulk carrier (~60k dwt)	Newbuild	Decarbonization by 2050	2024–2054	1.Future blend-in of carbon-neutral marine gas oil (MGO) 2. Future conversion to ammonia, along with blend-in of carbon-neutral MGO (pilot fuel)
Chemical tanker (~10k dwt)	Existing vessel	Decarbonization by 2050	2019–2049	1. Conversion to liquefied natural gas (LNG) and future blend-in of carbon-neutral LNG 2. Future blend-in of carbon-neutral MGO
General cargo vessel (~4k dwt)	Existing vessel	Decarbonization by 2070	2008–2046	1. Future blend-in of carbon-neutral MGO 2. Retrofit of Flettner rotors along with future blend-in of carbon-neutral MGO

For each generic ship case, we first present the baseline and target carbon intensity trajectory, followed by an assessment of each given compliance strategy before a decarbonization roadmap is developed. DNV's FuelPath Model[57] has been used for assessing all relevant compliance strategies in the generic ship case. Each generic ship case incorporates a few selected fuels and technology identified as relevant during workshops, but more could be considered (see Chapter 4 for an overview).

In the case studies, we consider tank-to-wake emissions of GHG emissions (carbon dioxide, methane, and nitrous oxide). Even though current IMO regulations on GHGs (e.g. CII rating and EEXI requirements) only cover tank-to-wake CO_2 emissions, we expect this to change in the future. We assume a GHG tank-to-wake emission reduction of 20% for LNG-fuelled vessels, compared with conventional vessels running on very low sulphur fuel oil (VLSFO). The actual reduction depends on the choice of LNG engine (technology dependent), operational profile (engine-load dependent). In the last years, reported performance data for LNG-fuelled engines indicate that an improvement in methane slip (e.g. Ushakov, 2019; GIE, 2021). We expect that this development will continue in the future. For more information about

55 https://www.maritimebergen.no/
56 Target carbon intensity trajectory specified in more detail in relevant subsections.
57 See DNV (2021a) for more information about the FuelPath Model.

methane slip, consider sources such as Lindstad et al. (2020), MAN (2019), and Sphera (2021). Apart from GHG emissions, other emission components from ships – for example, NOx and SOx emissions – should also be considered when assessing GHG compliance strategies. In particular, it is important to consider Emission Control Areas (ECAs), and local restrictions and incentives. When introducing alternative fuels, it will be vital to ensure that this will not lead to other unsustainable impacts in a lifecycle perspective. The IMO is working on guidelines to determine lifecycle CO_2 and GHG emission factors for all types of fuels, including biofuels and synthetic electrofuels. In this study, the terms *carbon-neutral MGO* and *carbon-neutral LNG* are used for fuels with similar properties to fossil MGO and LNG, but which are produced sustainably from biomass or renewable electricity. These fuels, in addition to ammonia, are assumed to have a GHG emission factor of zero in a tank-to-propeller perspective for the generic vessel cases. For more information on carbon-neutral fuels, see Chapter 4.

After a vessel enters its operational phase, its performance may become progressively worse due to factors such as hull fouling and engine performance deterioration. In the generic case studies, however, we assume that the vessel performance (in terms of energy consumption), remains constant throughout its lifetime.

6.1 Bulk carrier (60k dwt)

6.1.1 Step 1 – Define baseline, target trajectory, and compliance status

Baseline

The baseline vessel defined for this case is a 60k dwt bulk carrier, fuelled by VLSFO. This is a newbuild case, with planned delivery in 2024. Today, a modern such vessel operates with a carbon intensity in the order of ~4.7 gCO_2-eq/dwt-mile, based on reported emissions data, though the exact value will depend on factors such as operational profile of the vessel.

Target trajectory and compliance status

A target carbon intensity trajectory reaching zero in 2050 was identified as the most relevant carbon intensity trajectory[58] for this newbuild. This target trajectory reflects a market situation where cargo owners and financial institutions push for decarbonization beyond regulatory compliance (assuming the IMO's long-term GHG strategy is implemented through policy measures). In the period leading up to and including 2026, the carbon intensity trajectory is aligned with a 'C' rating according to CII rating requirements (see Chapter 3 for more information). Given this target trajectory, the baseline vessel is compliant for four years after its first year of operation, before decarbonization measures are needed (Figure 6-1).

[58] Note that even though that the adopted CII rating requirements only considers tank-to-wake CO_2 emissions, we are considering tank-to-wake GHG emissions in the generic vessel cases – including, for example, methane slip.

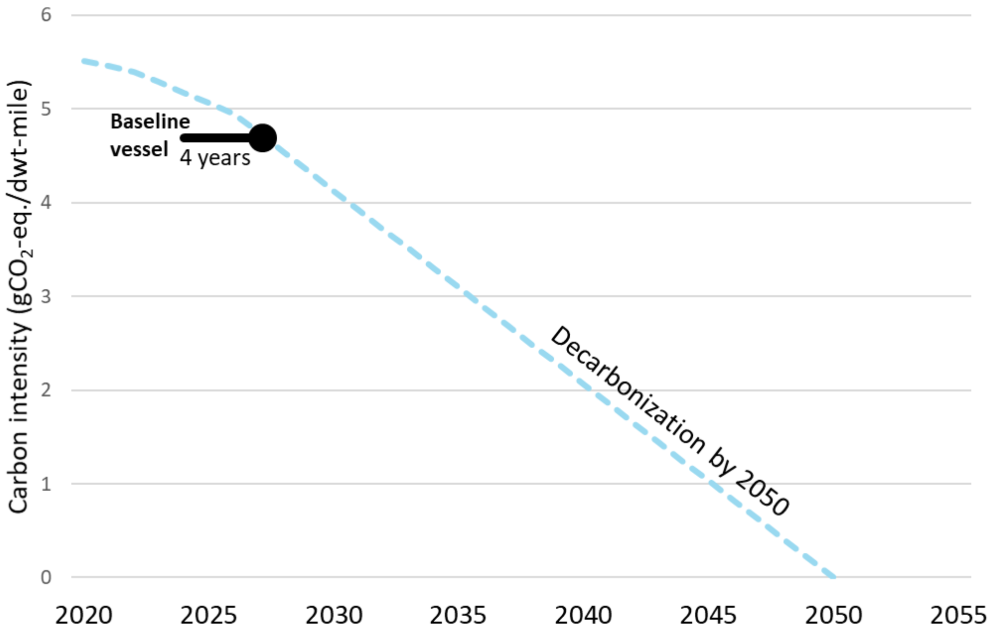

Figure 6-1 Target carbon intensity trajectory and compliance status of the baseline vessel in the bulk carrier (60k dwt) case.

6.1.2 Step 2 – Assessment of compliance strategy

Relative to the baseline presented earlier, Table 6-2 shows CO_2-eq reduction potential, and CAPEX for each of the measures deemed most relevant for the baseline vessel. The gate rudder and Air Lubrication System (ALS) are relatively immature measures, with few examples of real-life implementations on board ships. Therefore, both CO_2-eq reduction potential and additional CAPEX are uncertain.

Table 6-2 CO_2-eq reduction potential and additional CAPEX by measure.

Measure	CO_2-eq reduction potential (%)	Additional CAPEX (million USD[59])
LNG as fuel (Including ammonia-readiness[60])	20%	6.0
Gate rudder	5%	0.5
Slow steaming optimization	5%	0.0
ALS	4%	0.8

Based on this, we consider two newbuild options:

1. A conventional (fuelled by VLSFO) newbuild bulk carrier optimized for slow steaming, with an ALS, and a gate rudder.

[59] USD = US dollars
[60] Compatibility of LNG tank material with ammonia storage.

2. *DF LNG Fuel Ready (ammonia)*. A dual-fuel LNG newbuild bulk carrier optimized for slow steaming, with an ALS, and a gate rudder. The vessel has been prepared for a future retrofit to ammonia – a status described in the Handbook as Fuel Ready (ammonia).

For each of the newbuild options, one compliance strategy is identified and assessed, as described in Table 6-3.

Table 6-3 Description of compliance strategies explored in the bulk carrier (60k dwt) case.

Compliance strategy *Newbuild option*	Description of compliance strategy
Strategy 1 *MF conventional*	Future blend-in of carbon-neutral MGO to ensure compliance with carbon intensity trajectory.
Strategy 2 *DF LNG Fuel Ready (ammonia)*	Future conversion to ammonia, along with blend-in of carbon-neutral MGO (pilot fuel) to ensure compliance with target carbon intensity trajectory.

Figure 6-2 shows the annual cost for the two compliance strategies. Although *Strategy 2* has the highest CAPEX costs, both for the newbuild and later retrofit to ammonia, it has a significantly lower fuel expenditure as the vessel reaches its end of lifetime. Figure 6-3 shows the total discounted[61] cost associated with each compliance strategy (left), and total lifetime CO_2-eq emissions (right). Under the current economic assumptions, given in Appendix A, *Strategy 2* has a ~5% lower total discounted cost and 10.3% less total lifetime CO_2-eq emissions compared to *Strategy 1*. As a result, selecting *Strategy 2* as the compliance strategy makes the most sense from an economic and environmental perspective. This conclusion is subject to the given economic assumptions, and a prerequisite is that *Strategy 2* is a technically feasible compliance strategy and that ammonia and carbon-neutral MGO are available at bunkering locations in the future (this has not been assessed in detail for this case study). In order to determine the robustness of the strategy, its total discounted costs should be determined over many different fuel-price scenarios.

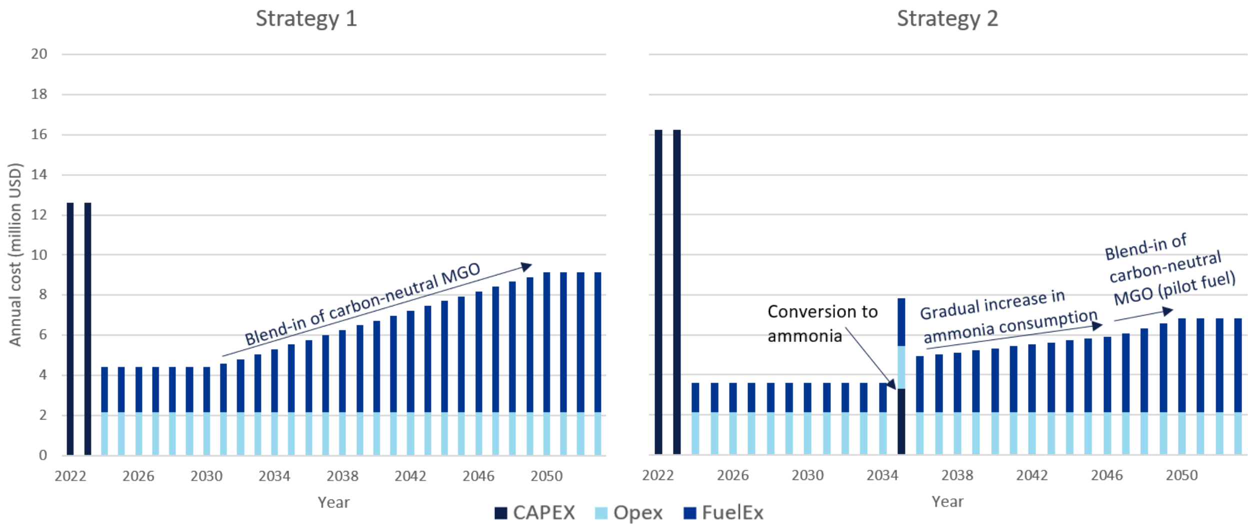

Figure 6-2 Break-down of annual cost for *Strategy 1* (left) and *Strategy 2* (right).

[61] Discount rate of 8% applied for all future cash flows.

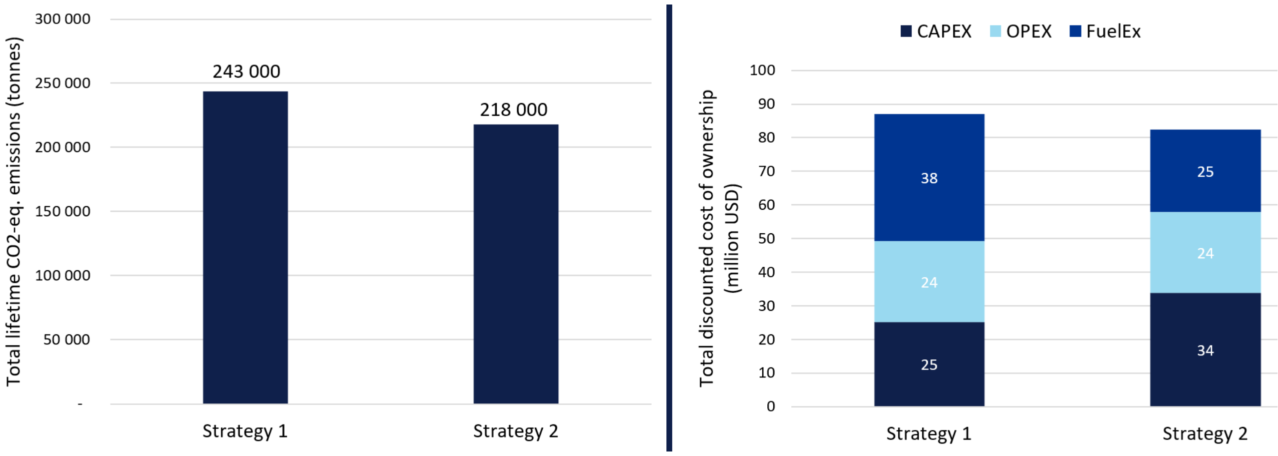

Figure 6-3 Lifetime CO_2-eq emissions (left) and break-down of total discounted lifetime cost (right), by compliance strategy.

6.1.3 Step 3 – Ship-specific roadmap for future carbon intensity compliance

Given the results from the previous section (assessment of compliance strategies), *Strategy 2* is the compliance strategy of choice. Figure 6-4 shows the carbon intensity pathway of the selected compliance strategy, until the ship's end of lifetime.

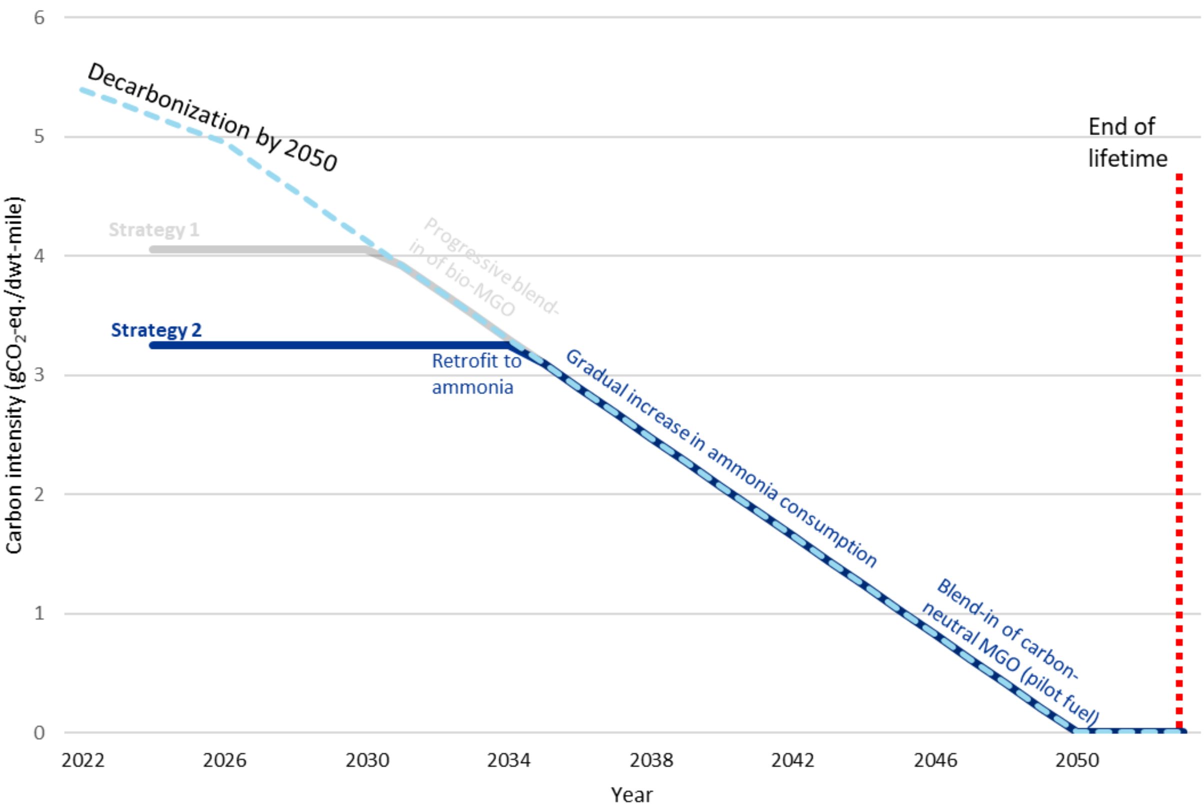

Figure 6-4 Illustration of carbon intensity for the selected compliance strategy (Strategy 2).

The shipowner must perform several actions and preparations to implement the selected decarbonization strategy. These are outlined in the decarbonization roadmap presented below, in the form of two items:

- Table 6-4 gives the decarbonization measures and time of implementation necessary to follow the carbon intensity pathway from Figure 6-4. Cost (CAPEX) and CO_2-eq reduction potential of each measure is also given. The volume of ammonia (and carbon-neutral pilot fuel) needed is also provided.
- Figure 6-5 gives a timeline with preparatory actions needed before implementation of decarbonization measures on board the vessel.

The roadmap looks far ahead into the future, until the vessel's expected end of lifetime. Therefore, it is recommended that the roadmap is kept up to date with the current drivers for decarbonization and the relevant technology space.

Table 6-4 The different measures and time of implementation needed for chosen compliance strategy.

	Measures to be implemented at newbuild stage (2024)	**Measures to be implemented in 2034**	**Measures to be implemented in 2047**
Hydrodynamics	ALS, gate rudder	-	-
Machinery	Slow steaming optimization	-	-
Fuel	DF LNG Fuel Ready (ammonia)	Retrofit to ammonia (Up to 8 000 t ammonia needed annually from 2047)	Blend-in of carbon-neutral MGO (pilot fuel) (Up to 800 t carbon-neutral MGO needed annually from 2050)
CO_2-eq reduction potential (%)	**~31%**	**~ 0%–76%**	**0%–100%**
Additional CAPEX (million USD)	**~ 7 million USD**	**~3 million USD**	**-**

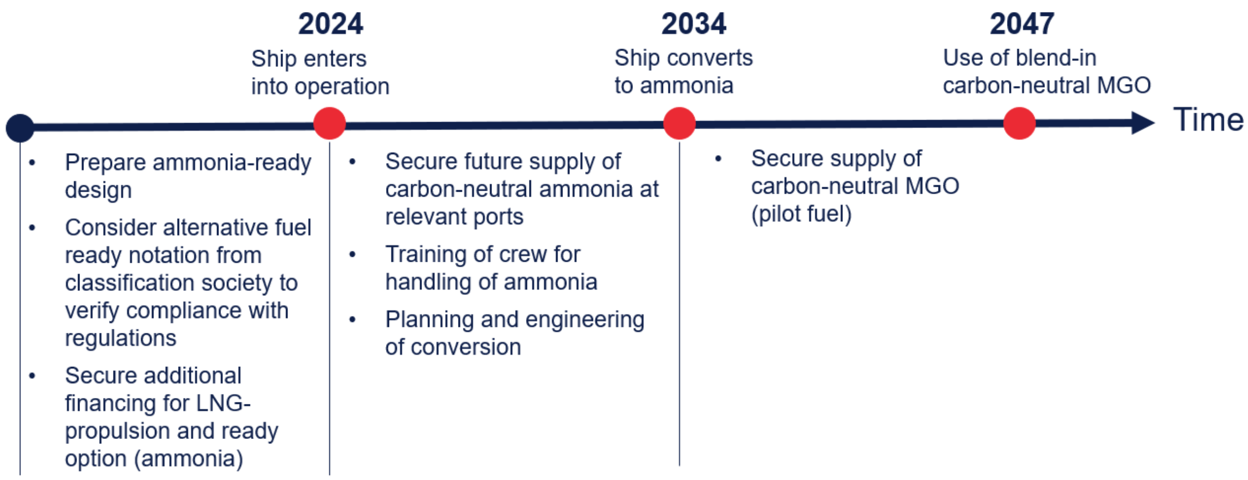

Figure 6-5 Timeline for important preparatory actions needed for implementation of strategy.

6.2 Chemical tanker (~10k dwt)

6.2.1 Step 1 – Define baseline, target trajectory, and compliance status

Baseline

The baseline vessel is an existing ship built in 2019 and running on VLSFO, but has been designed to facilitate a future conversion to LNG (i.e. LNG-ready). The vessel has already implemented several decarbonization measures, including draft optimization, weather routing, autopilot, and combinator optimization.

Today, the vessel has an operational carbon intensity in the order of ~15.9 gCO_2-eq/dwt-mile.

Target trajectory and compliance status

A target carbon intensity trajectory reaching zero in 2050 was identified as the most relevant for this generic ship case (see Figure 6-6), as this is in-line with the decarbonization ambitions of the shipowner involved in developing the generic vessel case. This target trajectory reflects a market situation where cargo owners and financial institutions push for decarbonization beyond regulatory compliance (assuming the IMO's long-term GHG strategy is implemented through policy measures). In the period leading up to and including 2026, the carbon intensity trajectory is aligned with a 'C' rating according to CII rating requirements (see Chapter 3 for more information). Given this target trajectory, the generic case vessel will be compliant until 2029, at which point decarbonization measures are needed.

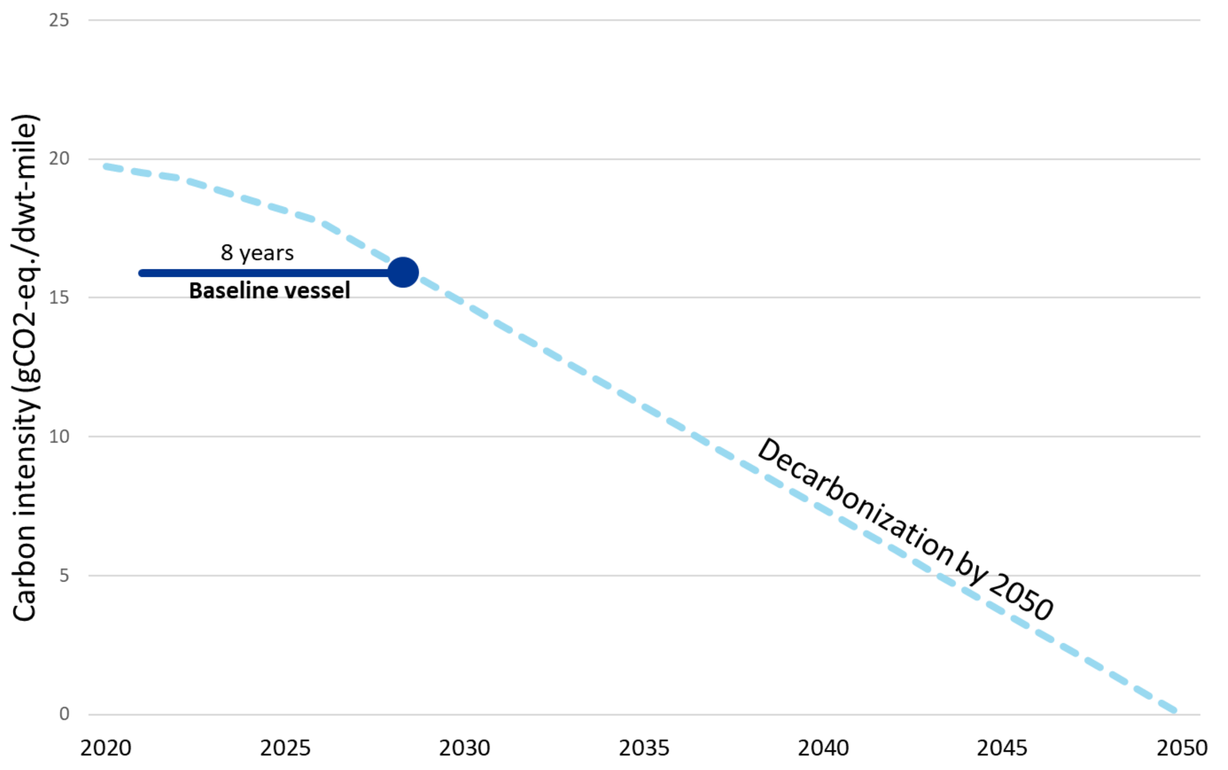

Figure 6-6 Target carbon intensity trajectory and compliance status of baseline vessel (~10k dwt chemical tanker).

6.2.2 Step 2 – Assessment of compliance strategy

As the baseline vessel has taken steps at the newbuilding stage to prepare for future conversion to LNG (i.e. LNG-ready), such a conversion is seen as a natural decarbonization measure. For simplicity, this is the only decarbonization measure considered in this case, apart from blend-in of carbon-neutral fuel (see Table 6-5). In reality, energy-efficiency measures could be considered either in combination with conversion to LNG or as standalone measures.

Table 6-5 CO_2-eq reduction potential and additional CAPEX by measure.

Measure	CO_2-eq reduction potential (%)	Additional CAPEX (million USD)
LNG as fuel	20%	3.2

Based on the above, two compliance strategies are identified and assessed as described in Table 6-6.

Table 6-6 Description of compliance strategies explored in the chemical tanker case.

Compliance strategy	Description of compliance strategy
Strategy 1	Conversion to LNG in 2022. Future blend-in of carbon-neutral LNG to ensure compliance with target carbon intensity trajectory.
Strategy 2	Future blend-in of carbon-neutral MGO to ensure compliance with carbon intensity trajectory.

Figure 6-7 shows the break-down of annual cost for the two compliance strategies. Although *Strategy 2* has the highest CAPEX costs, due to the conversion to LNG-propulsion, it has a significantly lower fuel expenditure as the vessel reaches its end of lifetime.

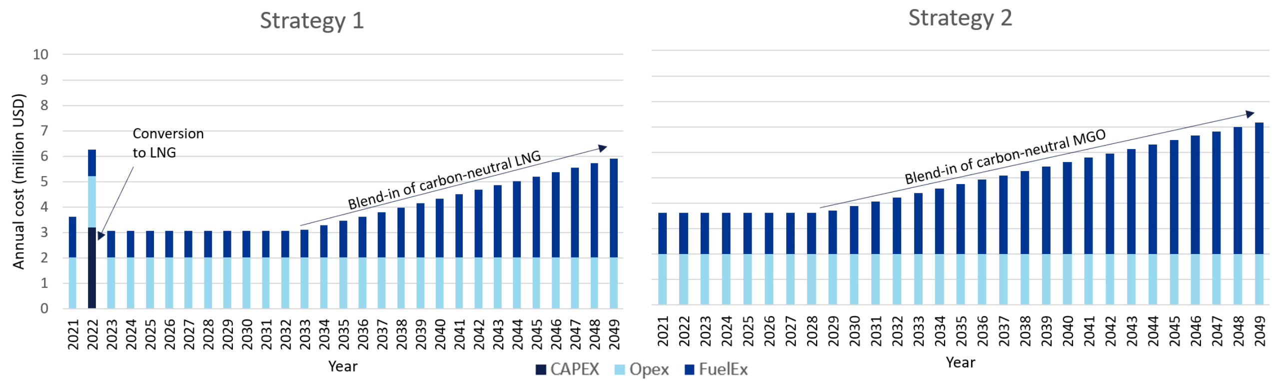

Figure 6-7 Break-down of annual cost for *Strategy 1* (left) and *Strategy 2* (right).

Figure 6-8 shows the total discounted[62] cost associated with each compliance strategy (left), and total lifetime CO_2-eq emissions (right). Under the current economic assumptions, given in Appendix A, *Strategy 1* has a ~13% lower total discounted cost and 9% less total lifetime CO_2-eq emissions compared with *Strategy 2*. As a result, selecting *Strategy 1* as the choice of compliance strategy makes the most sense from an economic and environmental perspective. This conclusion is subject to the given economic assumptions, and sensitivity studies should be performed to make this decision more robust.

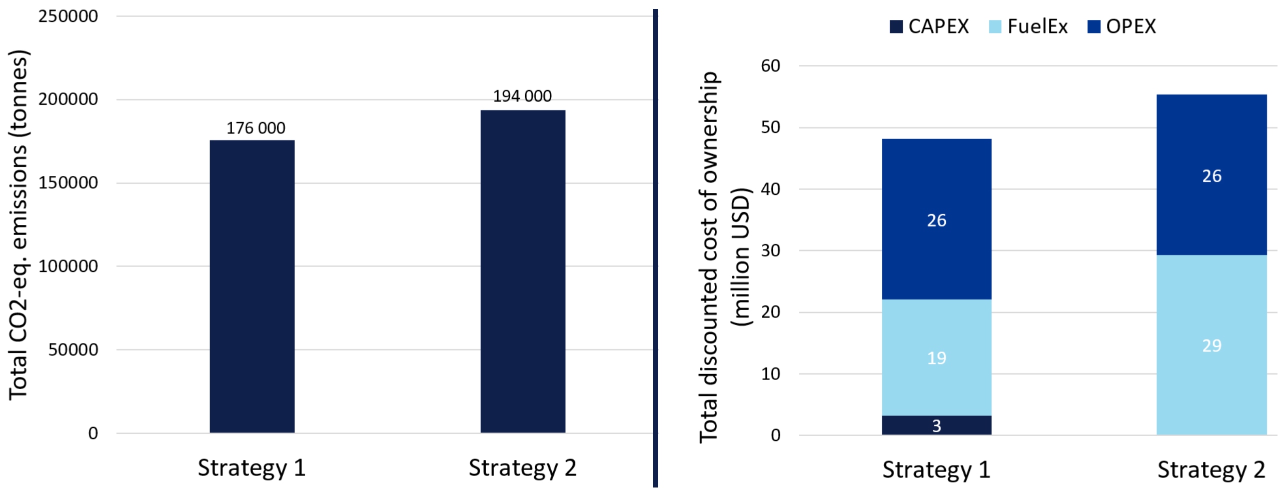

Figure 6-8 Lifetime CO_2-eq emissions (left) and break-down of total discounted lifetime cost (right), by compliance strategy.

[62] Discount rate of 8% applied for all future cash flows.

6.2.3 Step 3 – ship-specific roadmap for future carbon intensity compliance

Given the results from the previous section (assessment of compliance strategies), *Strategy 1* – converting to LNG - is the compliance strategy of choice. Figure 6-9 shows the carbon intensity pathway of the selected compliance strategy, until the ship's expected end of lifetime.

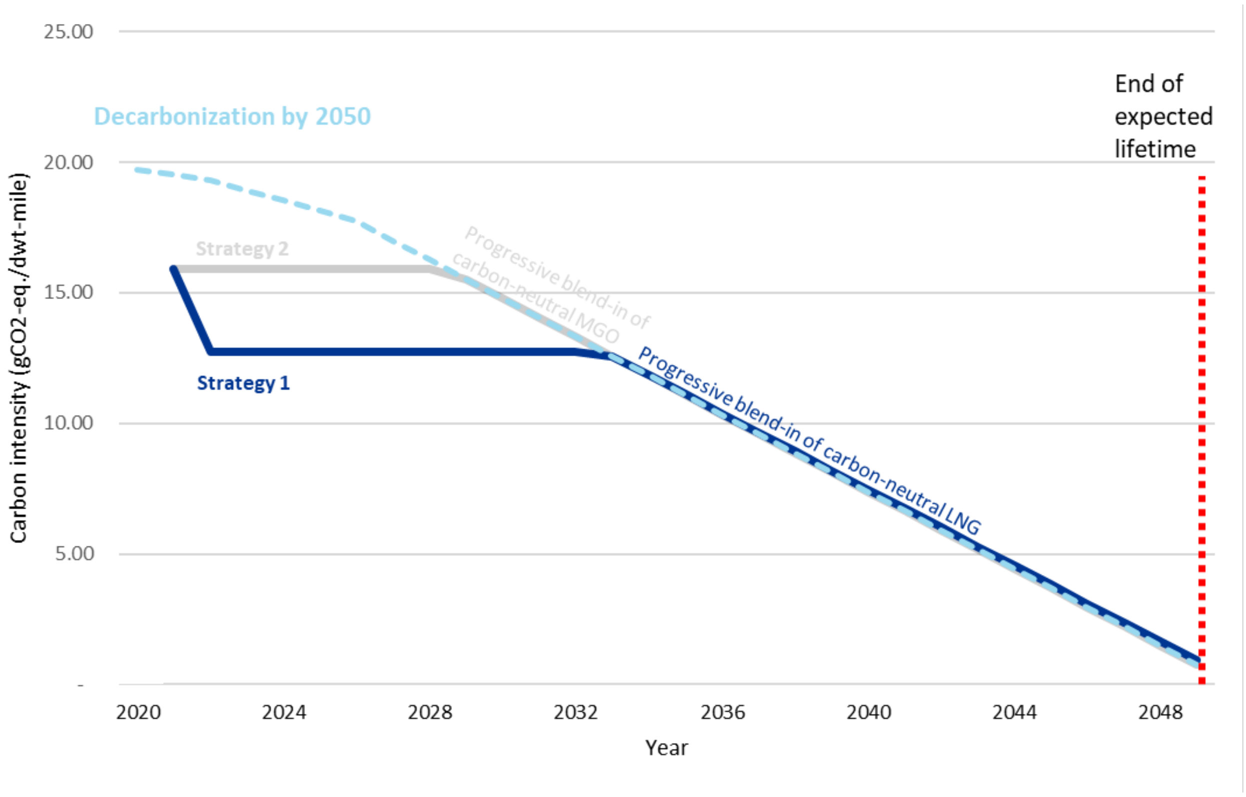

Figure 6-9 Illustration of carbon intensity for the selected compliance strategy (*Strategy 1*).

The shipowner must perform several actions and preparations to implement the selected decarbonization strategy. These are outlined in the decarbonization roadmap presented below, in the form of two items:

- Table 6-7 gives the decarbonization measures and time of implementation necessary to follow the carbon intensity pathway from Figure 6-9. Cost (CAPEX) and CO_2-eq reduction potential of each measure is also given. The volume of carbon-neutral LNG needed is also provided.
- Figure 6-10 gives a timeline with preparatory actions needed before implementation of decarbonization measures on board the vessel.

The roadmap looks far ahead into the future, until the vessel's expected end of lifetime. Therefore, it is recommended that the roadmap is kept up to date with the current drivers for decarbonization and the relevant technology space.

Table 6-7 The different measures and time of implementation needed for selected compliance strategy.

	Measures to be implemented in 2022	Measures to be implemented in 2033
Fuel	Conversion to LNG	Substitution of fossil LNG with carbon-neutral LNG (Up to 2 500 t carbon-neutral LNG needed annually in 2049)
CO_2-eq reduction potential (%)	**∑~ 20%**	**0%–93%**
Additional CAPEX (million USD)	**∑~ 3 million USD**	-

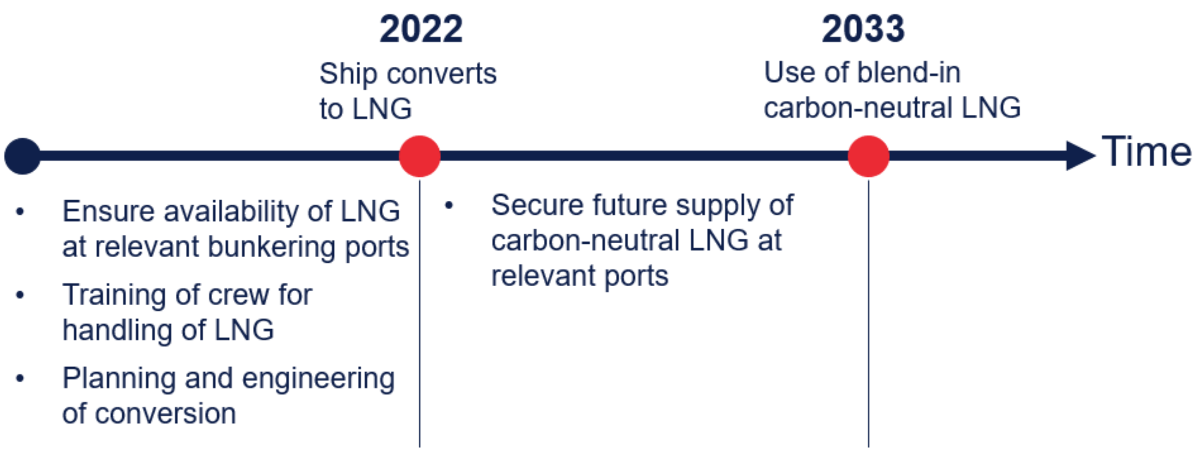

Figure 6-10 Timeline for important preparatory actions needed for implementation of roadmap.

6.3 General cargo vessel (4k dwt)

6.3.1 Step 1 – Define baseline, target trajectory, and compliance status

Baseline

The baseline vessel is an existing ship built in 2008 and running on VLSFO. The vessel is already operating at a low speed (<10 knots (kn)), and further speed reduction is likely not feasible from a technical and commercial perspective. Today, the vessel has an operational carbon intensity in the order of ~19.3 gCO_2-eq/dwt-mile.

Target trajectory and compliance status

A target carbon intensity trajectory reaching zero in 2070 (although the vessel is expected to have its last operational year in 2046) was identified as the most relevant carbon intensity trajectory for this newbuild (see Figure 6-11). This trajectory can represent a minimum regulatory compliance trajectory assuming the IMO's current long-term GHG strategy is implemented through policy measures. This trajectory was picked since the vessel is below 5,000 GT and is hence not subject to CII rating and enhanced SEEMP requirements (reference to Chapter 3, Table 3-1). Consequently, as far as international decarbonization policy measures are concerned, the regulatory driver for this vessel is not as strong as for other ships above 5,000 GT. The given target trajectory, *Decarbonization by 2070*, is based on the CII reference line for bulk carriers and is aligned with a 'C' rating between 2023 and 2026, before going linearly towards zero in 2070. It should be noted that the CII reference line has been constructed based on data for vessels of 5,000 GT and above. As such, the CII reference line is not necessarily representative of the performance of the general cargo vessel assessed in this generic ship case. Under the given target carbon intensity trajectory, the baseline vessel is compliant until 2034.

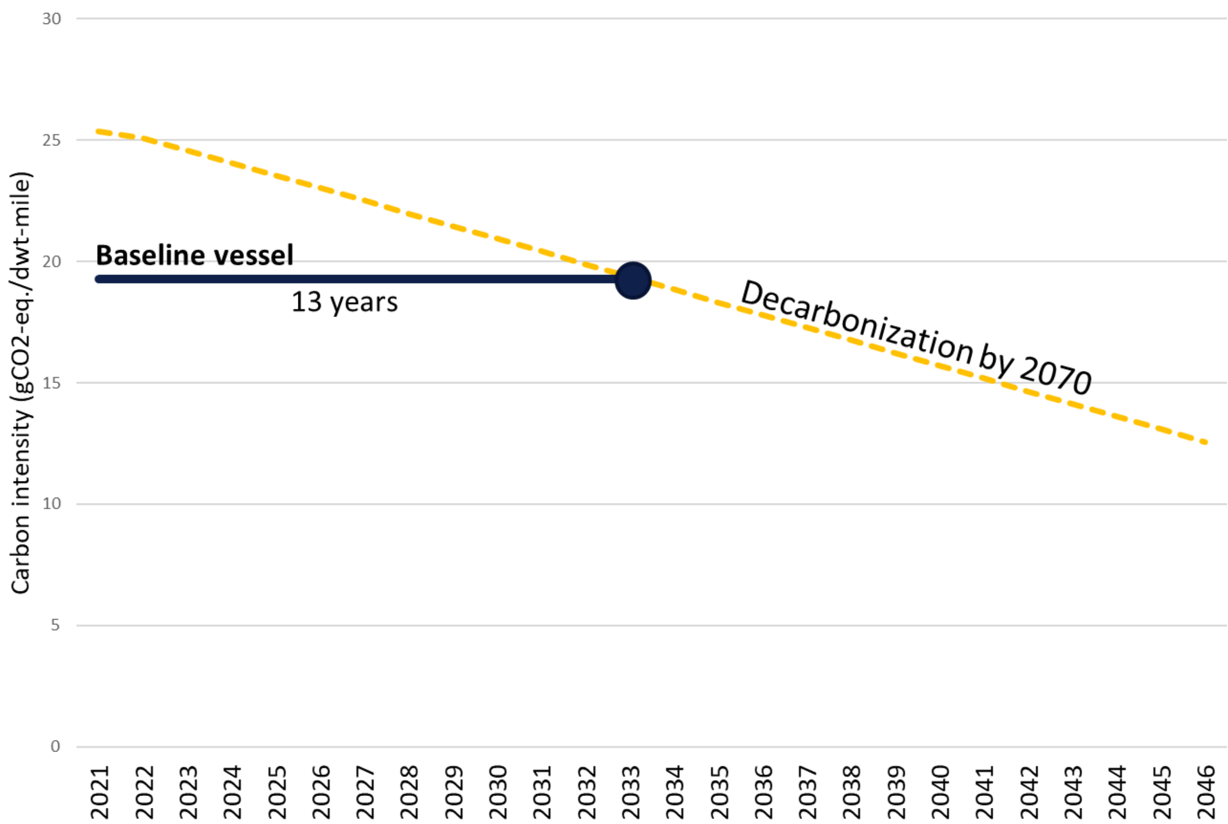

Figure 6-11 Target carbon intensity trajectory and compliance status of baseline vessel (~4k dwt bulk carrier).

6.3.2 Step 2 – Assessment of compliance strategy

In this case we consider use of energy harvesting measures, and more specifically, Flettner rotors. Since the baseline vessel is conventional and has not been prepared for any future conversion of fuel, alternative fuels have not been considered as decarbonization measures (other than use of compatible blend-in fuel). Retrofitting two Flettner rotors is estimated to cost approx. USD 800,000 for this vessel, with an assumed saving of 12% CO_2-eq. The saving potential of the Flettner rotor will in reality depend on factors such as weather conditions and the speed of the vessel.

Each compliance strategy assessed is described in Table 6-8.

Table 6-8 Description of compliance strategies explored in this generic vessel case.

Compliance strategy	Description of compliance strategy
Strategy 1	Future blend-in of carbon-neutral MGO to ensure compliance with target carbon intensity trajectory.
Strategy 2	Retrofit of Flettner rotor in 2022, combined with future blend-in of carbon-neutral MGO to ensure compliance with carbon intensity trajectory.

Figure 6-12 shows the break-down of annual cost for the two compliance strategies. Although, *Strategy 2* has the highest CAPEX costs, due to the retrofit of Flettner rotors in 2022, it has a lower fuel expenditure as the vessel reaches its end of lifetime, due to lower fuel consumption.

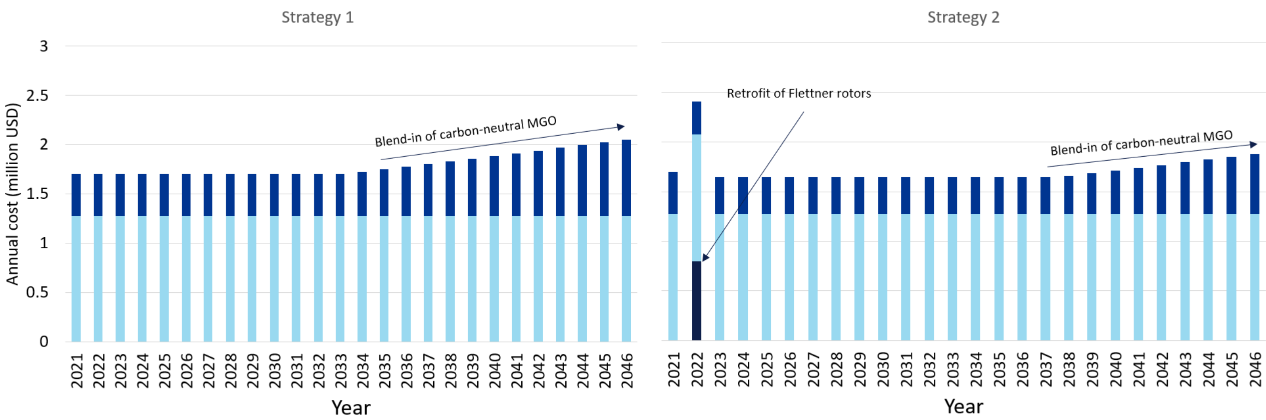

Figure 6-12 Break-down of annual cost for *Strategy 1* (left) and *Strategy 2* (right).

Figure 6-13 shows the total discounted[63] cost associated with each compliance strategy (left), and total lifetime CO_2-eq emissions (right). Under the current economic assumptions, given in Appendix A, *Strategy 2* has a ~1% lower total discounted cost and a 7% lower total lifetime CO_2-eq emissions compared with *Strategy 1*. As a result, selecting *Strategy 2* as the choice of compliance strategy, makes the most sense from an economic and environmental perspective. This conclusion is subject to the given economic assumptions, and sensitivity studies should be performed to make this decision more robust.

[63] Discount rate of 8% applied for all future cash flows.

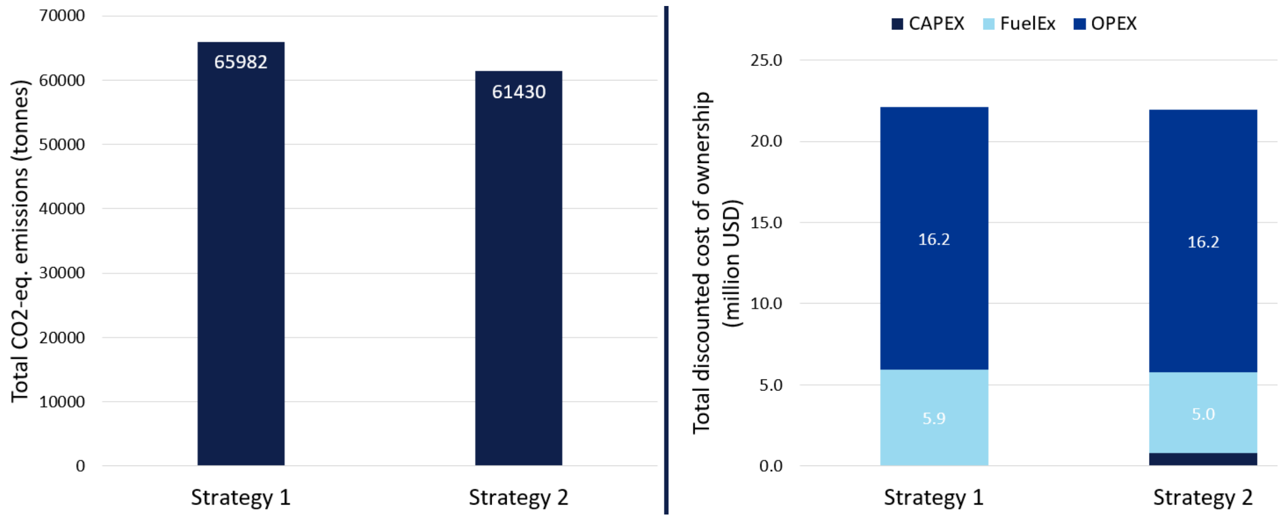

Figure 6-13 Lifetime CO_2-eq emissions (left) and break-down of total discounted lifetime cost (right), by compliance strategy.

6.3.3 Step 3 – ship-specific roadmap for future carbon intensity compliance

Given the results from the previous section (assessment of compliance strategies), *Strategy 2* is the compliance strategy of choice. Figure 6-14 shows the carbon intensity pathway of the selected compliance strategy, until the ship's end of lifetime.

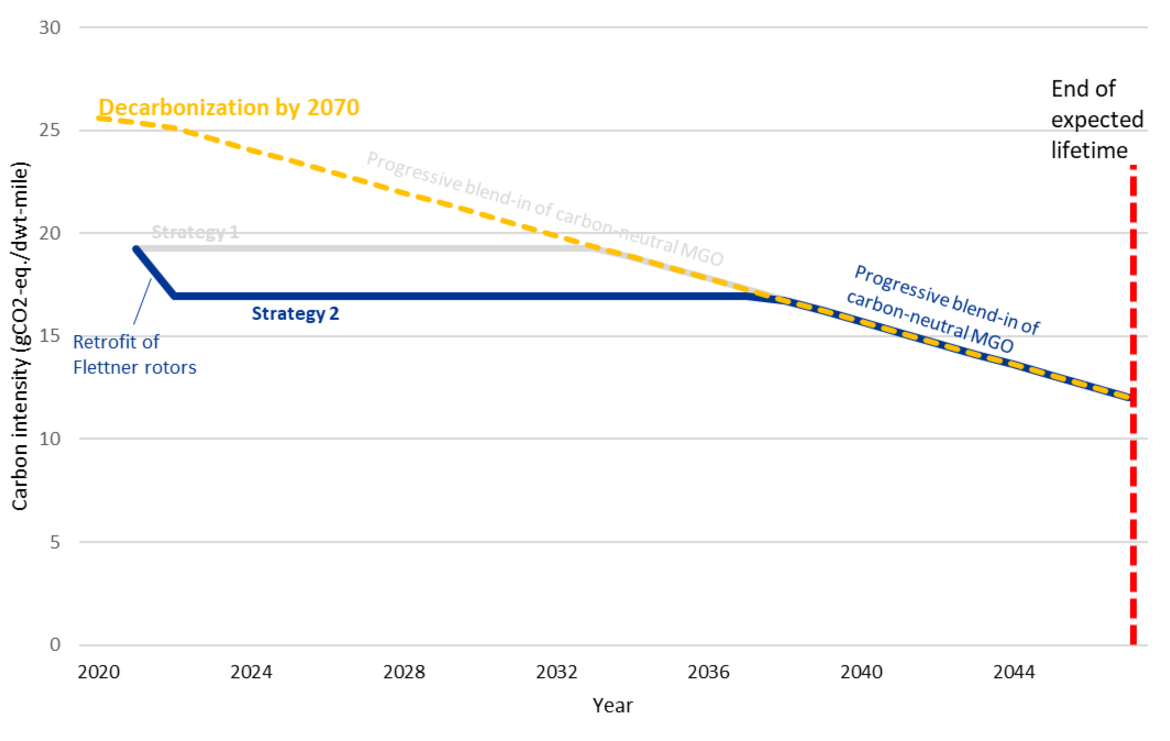

Figure 6-14 Illustration of carbon intensity for the selected compliance strategy (*Strategy 2*).

The shipowner must perform several actions and preparations to implement the selected decarbonization strategy. These are outlined in the decarbonization roadmap presented below, in the form of two items:

- Table 6-9 gives the decarbonization measures and time of implementation necessary to follow the carbon intensity pathway from Figure 6-14. Cost (CAPEX) and CO_2-eq reduction potential of each measure is also given. The volume of carbon-neutral MGO is also provided.
- Figure 6-15 gives a timeline with preparatory actions needed before implementation of decarbonization measures onboard the vessel.

The roadmap looks far ahead into the future, until the vessel's expected end of lifetime. Looking this far ahead in time inherently involves great uncertainty. Therefore, it is recommended that the roadmap is kept up to date with the current drivers for decarbonization and the relevant technology space.

Table 6-9 The different measures and time of implementation needed for selected compliance strategy.

	Measures to be implemented in 2022	Measures to be implemented in 2037
Energy harvesting	Retrofit of Flettner rotors	
Fuel		Substitution of fossil VLSFO with carbon-neutral MGO (Up to 200 t carbon-neutral MGO needed annually in 2048)
CO_2-eq reduction potential (%)	∑~ 12%	0%–30%
Additional CAPEX (million USD)	∑~ 1 million USD	

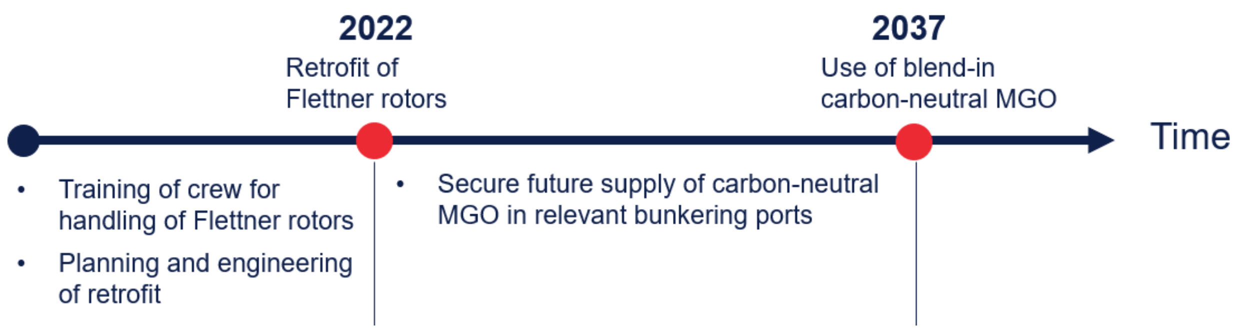

Figure 6-15 Timeline for important preparatory actions needed for implementation of roadmap.

6.4 Handling uncertainties

To make the results from the cases more robust, their sensitivities to uncertainties in key variables should be investigated as part of Step 2. Key input variables for developing the compliance strategy and the roadmaps are projections of fuel prices and CO_2 price, assumed technology costs and reduction potentials of the various measures included, as well as the discounting rate. By varying, for example, the range of fuel and CO_2 prices and technology costs, the results can provide a better picture of the financial robustness of the compliance strategy.

In this section, we exemplify how uncertainty in one key factor can be analysed. In our case results we have assumed that CO_2 prices are zero. In the following we explore the impact of a CO_2 price on the case results.

As noted in Chapter 3, the IMO as part of its medium- and long-term policy measures, could consider a CO_2 pricing scheme in the future to reduce the price-gap between carbon-neutral fuels and fossil fuels. Such a mechanism would likely require a new convention to adopted in the IMO, therefore it is reasonable to assume that it would be hard to implement before the latter half of this decade. Also, the EU, is considering extending its Emissions Trading System to include maritime transport. As such, there is a high likelihood that a significant share of the world fleet will be subject to CO_2 pricing in the not-too-distant future.

To explore the impact of such a pricing scheme on the economic analysis performed for the generic vessel cases earlier in the chapter, we have calculated the total discounted cost of ownership for all cases given two different levels of CO_2 pricing starting in 2030: *100 USD/tCO₂,* and *300 USD/tCO₂*. These are consistent with the range of CO_2 prices stated by some stakeholders as being necessary for achieving decarbonization goals (e.g. Maersk[64], OECD[65], the Norwegian government[66], Trafigura (2020), and DNV GL (2020a), though some stated CO_2 prices are not specifically applicable for shipping. The results from the economic assessment are presented in Figure 6-16, Figure 6-17, and Figure 6-18.

We observe from the Figures that all the cost associated with all the evaluated strategies increases with increasing CO_2 price. Furthermore, the cost of the strategies selected for each generic vessel case remains lower than the alternative compliance strategies. The reason for this is that the compliance strategy with lowest lifetime CO_2-eq emissions was picked and implemented into the roadmaps. There is an increasing difference between the selected and the competing strategies; but since we are assuming that the CO_2 pricing does not come into force before 2030, it has a limited impact on costs. The reason is that no compliance strategy makes a great difference in terms of annual CO_2-eq emissions post-2030.

64 https://shipandbunker.com/news/world/633414-maersk-proposes-450mt-carbon-tax-for-bunker-fuel
65 https://www.oecd.org/tax/tax-policy/effective-carbon-rates-2021-highlights-brochure.pdf
66 https://bellona.org/news/ccs/2021-02-norway-proposes-e200-per-ton-co2-tax-by-2030

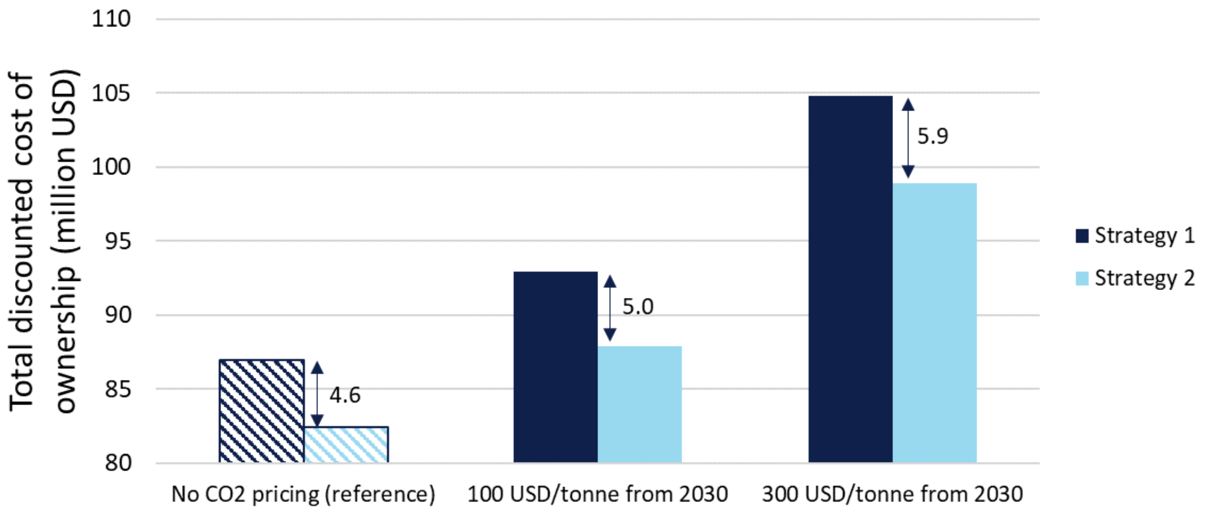

Figure 6-16 Impact of CO_2 pricing on total discounted cost of ownership for the bulk carrier (~60k dwt) generic vessel case.

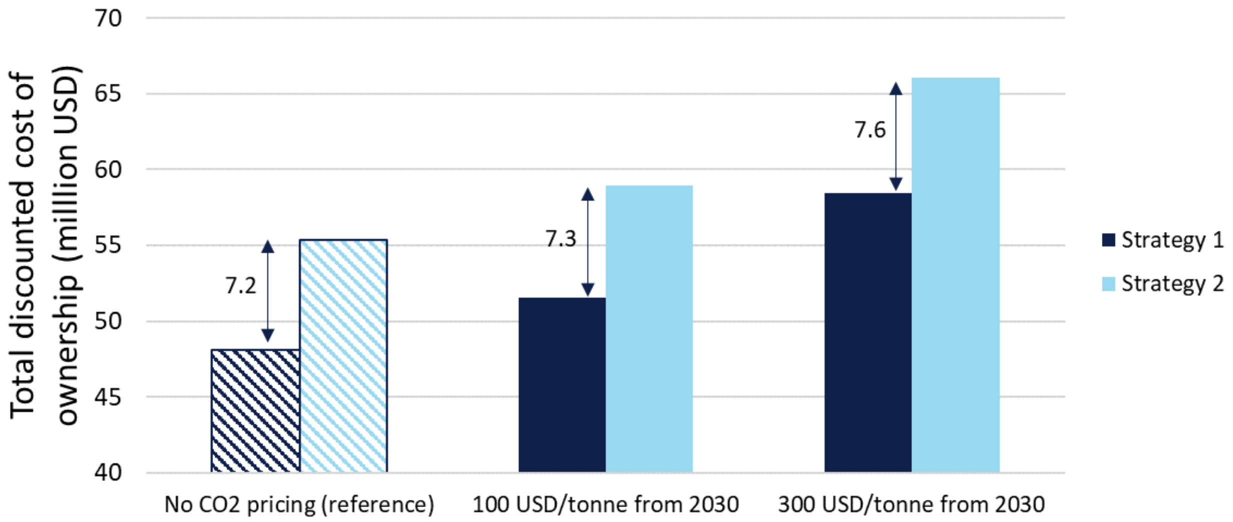

Figure 6-17 Impact of CO_2 pricing on total discounted cost of ownership for the chemical tanker (~10k dwt) generic vessel case.

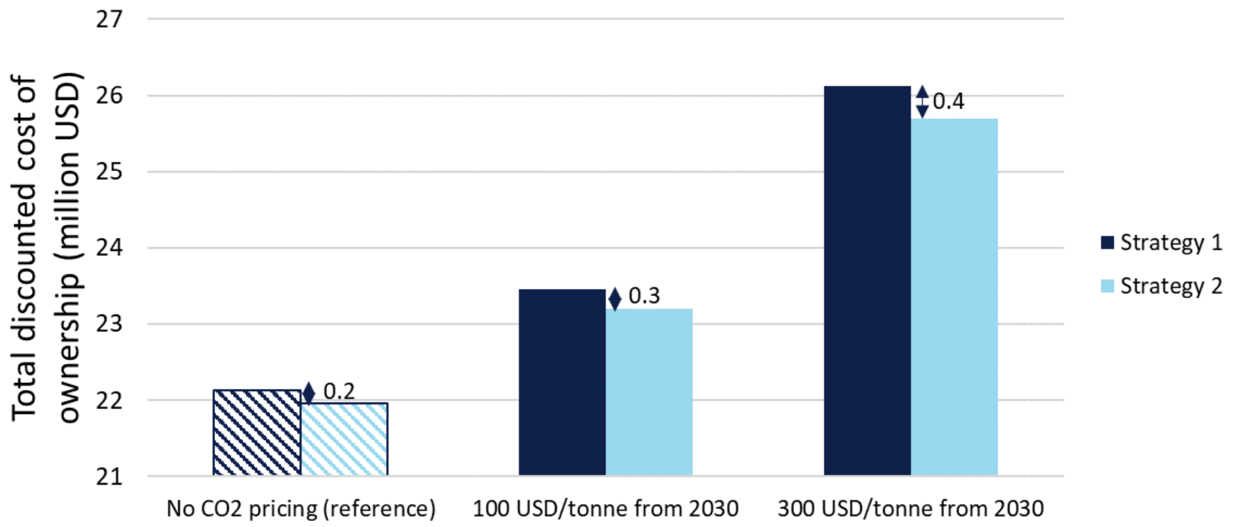

Figure 6-18 Impact of CO_2 pricing on total discounted cost of ownership for the general cargo (~4k dwt) generic vessel case.

COURSE TO ZERO