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Marine Science and Technology Management

**“Cost-benefit analysis of the Onboard Carbon
Capture System(OCCS) for the decarbonization of
shipping ”**

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Piraeus as part of the requirements for obtaining the master's degree in
“Marine Science and Technology Management“

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Abstract

In the thesis report below a cost benefit analysis of the OCCS system is going to be performed for two categories of vessels, tankers and bulkers.

The cost benefit analysis will take place in two scenarios. In the first the 2-tier levy proposed from IMO will not be implemented.

In the second scenario the 2-tier levy will be implemented.

The goal of this thesis is to research the conditions, in both scenarios, upon which this system will create an ROI beneath 10 years making this installation a sound investment for a company.

Keywords

CO₂, Cost-Benefit Analysis, Decarbonization, OCCS

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Abbreviations

Carbon Dioxide(CO₂)

Carbon Capture and Storage (CCS)

Carbon Intensity Indicator(CII)

Energy Efficiency Design Index (EEDI)

Energy Efficiency Existing Ship Index (EEXI)

EU Emissions Trading System (EU ETS)

European Union(EU)

Exhaust Gas Cleaning System(EGCS)

Greenhouse Gas(GHG)

Gross Tonnage (GT)

Onboard Carbon Capture and Storage (OCCS)

Synthesis Gas (Syngas)

Tank-to-Wake(TtW)

United Nations(UN)

1. Carbon Dioxide(CO₂)

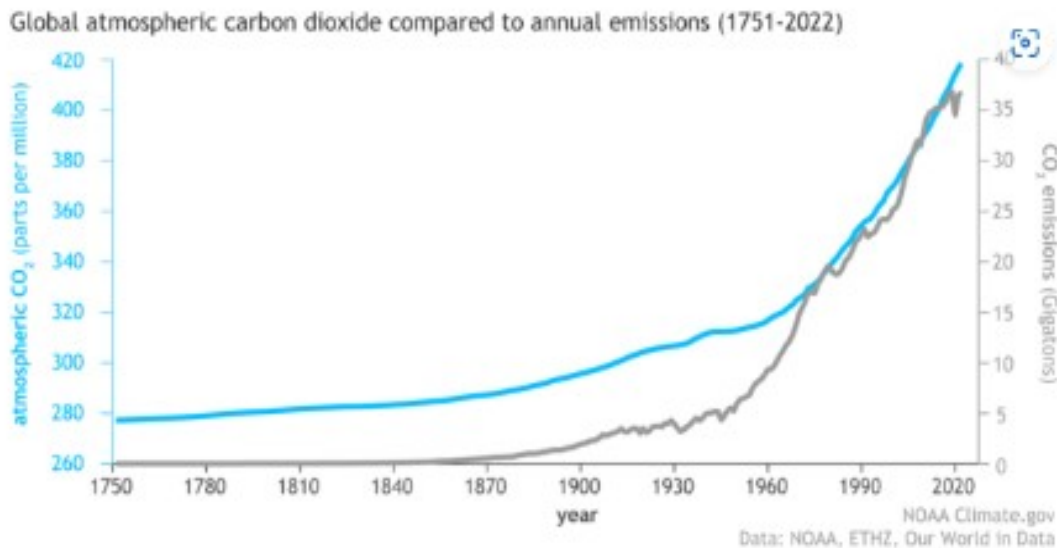
Carbon Dioxide(CO₂) is an essential part of our planet's atmosphere. It is an irremovable part of life on our planet since it is the basic ingredient of photosynthesis. But it is also a greenhouse gas, maybe the most important one.

CO₂ does not exist only in the atmosphere, it also dissolves into sea water, and while doing so it produces carbonic acid and thus raises the acidity of the sea.

1.1 The problem of the rise of CO₂ in the atmosphere

The percentage of CO₂ on our planet has remained the same for thousands of years. However, following the Industrial Revolution, the percentage of CO₂ in our planet's atmosphere is rising continuously. It is estimated that at about 1750 the atmosphere concentration was about 280ppm(I.C. Prentice et al., 2001) while in 2023 it reached almost 420ppm.

In the past the rates of CO₂ in earth's atmosphere have also risen from natural causes. But since 1970 the rate at which the CO₂ is increasing, is estimated to be 100 times



faster¹.

¹<https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide>

This rise in CO₂ might have catastrophic effects on our planet. Normally CO₂ presence in the atmosphere will cause a part of the heat radiating from our planet to disperse in all directions while a part of it will bounce back to earth. In that way it helps regulate the planet's temperature.

In the meantime, it is calculated that about 40% of the CO₂ that humans have created in the past 2 centuries has been absorbed by sea (Caldeira, Ken, et al.2005).

When the CO₂ percentage rises, the concentration will primarily take place over the Northern Hemisphere. This will initiate a cascade effect, the more CO₂ rises the more the ocean temperature will rise, thus lowering the ocean's capability to hold CO₂. So, it will release more to the atmosphere causing the temperature to rise even more.

1.2 EU and UN Policies against Climate Change

In an attempt to minimize the damage humans cause to the environment both the UN as a whole and IMO as the maritime sector of the UN, but also EU have taken a series of actions.

1.2.1 United Nations(UN) and IMO policies

UN developed in 1992 the United Nations Framework Convention on Climate Change. This convention established a framework to stop climate change. At this point there are 197 Parties to this convention².

This led in the Kyoto Protocol³, in 1997, that legally binds country Parties to emission reduction targets as long as they are developed. This Protocol had 2 periods during which the countries were trying to achieve their goals. The first period was between 2008 and 2012, and the second period started in 2013 and lasted till 2020. At this Protocol the Parties numbered 192.

² <https://unfccc.int/process/the-convention/history-of-the-convention#Essential-background>

³ https://unfccc.int/kyoto_protocol

The Paris Agreement⁴ that was adopted in 2015 is the most recent step under the UN to address the climate change problem. The goals set by this agreement is to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursue efforts “to limit the temperature increase to 1.5°C above pre-industrial levels.” To implement the Paris Agreement an economic and social transformation, based on the best available science is going to be required.

As part of UN, IMO has decided to develop a strategy on the reduction of the GHG emissions from ships coming into effect from the 1st of January 2023, in support of Goal 13 set by UN Sustainable Development⁵. A part of this strategy is the reduction of the CO₂ emissions per transport work, by 40% at least, by 2030, when it comes to international shipping. The emissions are to be compared with the emissions recorded in 2008. On top of that the end goal is to reach a net-zero emissions when it comes to GHG by 2050, at the latest.

For this to happen all existing vessels above 400 gross tonnages (GT) must attain an Energy Efficiency Existing Ship Index (EEXI)⁶. Meanwhile to ensure that there will be an annual reduction factor called Carbon Intensity Indicator(CII) was also established.

Another policy for new buildings is the creation of the Energy Efficiency Design Index (EEDI)⁷.

Finally, the most recent policies introduced by IMO in MEPC 83⁸, include a two-tier levy, pending an adoption vote during MEPC 84.

⁴ <https://unfccc.int/process-and-meetings/the-paris-agreement>

⁵ <https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx>

⁶ <https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx#:~:text=What%20is%20a%20Carbon%20Intensity,within%20a%20specific%20rating%20level.>

⁷ <https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx#:~:text=The%20EEDI%20provides%20a%20specific,parameters%20for%20a%20given%20ship.>

⁸ <https://www.imo.org/en/mediacentre/meetingsummaries/pages/mepc-83rd-session.aspx>

1.2.2 EU policies

At the same time to address the problem of the greenhouse gas(GHG) emissions European Union(EU) since 2005 is implementing the EU Emissions Trading System (EU ETS)⁹, a system that includes not just all EU countries but also Iceland, Liechtenstein and Norway, and is linked to the Swiss ETS.

EU ETS trades emissions from industries in the electricity and heat generation, industrial manufacturing and aviation sectors and since 2024 the maritime transportation sector.

2. Carbon Capture and Storage (CCS)

Despite the widespread use of renewable energy sources, the use of fossil fuels is still the main source of energy worldwide. For companies to be able to meet the criteria established by both the UN and EU and protect the environment, the use of modern technologies to both capture and store the CO₂ that is produced is becoming increasingly popular. Especially since the technologies that are currently available can reduce CO₂ emissions by as much as 95%(Wilberforce, T., et al., 2021).

In land-based companies this procedure is mainly used in power plants and cement factories and consists of 3 stages.

The first stage is the capture of CO₂ from the stream, the second involves the transportation of the CO₂ captured to facilities where it can be temporarily stored and the third step includes the isolation of the CO₂ captured for long term storage.

2.1 Carbon Capture technologies

Modern technologies have provided a wide range of processes with which one can remove the CO₂ from the gases subsequently released into the environment. The technologies that are currently in use are mentioned below.

⁹ https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/what-eu-ets_en

2.1.1 Post-Combustion CC

With this process and depending on the fuel type used to create the flue gas, the CO₂ recovery is between 80-90%. It is mainly used in industrial furnaces and cement kilns, where a large-scale fossil fuel combustion is used.

For the process to take place chemical solvents are utilized, amine being one of them. The flue gas is initially cooled to somewhere between 40 and 60 degrees Celsius. Then the CO₂ bonds in the flue gas interacts with the amine, as the gas is introduced in the absorber and they form chemical bonds. The final stage of this process involves the amine, which is now bound with CO₂, to be heated to 100-140 degrees Celsius. That way, the amine, is regenerated while CO₂ is released and collected.

This process requires a lot of energy and thus creates an efficiency penalty that has to be taken into account.

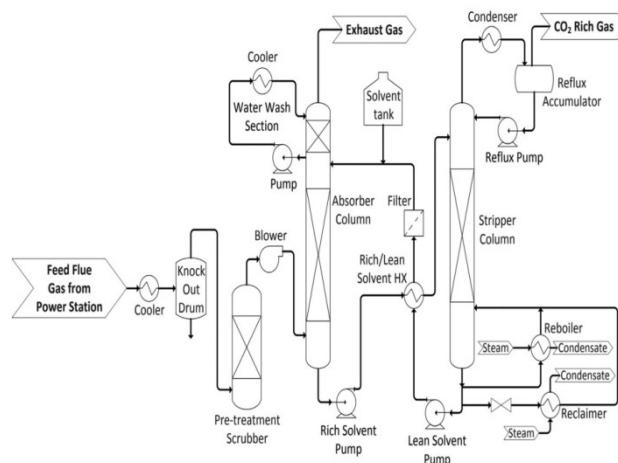


Fig. 3. Post-combustion carbon capture process layout (Bui et al., 2013).

(Bui, M. et al. 2013)

When it comes to the shipping industry, this technology is the one that can be retrofitted to existing engine design with no need for large scale changes.¹⁰

2.1.2 Pre-Combustion CC

This process involves the production of a mixture of carbon monoxide and hydrogen, called synthesis gas (syngas), from reforming the fuel, which is then

¹⁰ [https://www.lr.org/en/knowledge/horizons/march-2023/carbon-captures-role-in-maritimes-energy-transition/#:~:text=Carbon%20Capture%20and%20Storage%20\(CCS\)%20systems%20are%20technologies%20that%20can,fossil%20fuels%20in%20power%20generation.](https://www.lr.org/en/knowledge/horizons/march-2023/carbon-captures-role-in-maritimes-energy-transition/#:~:text=Carbon%20Capture%20and%20Storage%20(CCS)%20systems%20are%20technologies%20that%20can,fossil%20fuels%20in%20power%20generation.)

followed by the CO₂ separation. The whole process(Nazir, S.M. et al, 2019) aims in the production of hydrogen which is then used as fuel giving as an output of the combustion water, while CO₂ is captured. This process also involves the elimination of sulfur along with any particulate matter that exists.

2.1.3 Oxy-Fuel combustion CC

Instead of atmospheric air this technic involves pure Oxygen as the combustion element alongside fossil fuels. By introducing pure oxygen, flue gas consists mainly of CO₂ and water. Some acid gas from the presence of sulfur in the fossil fuels is removed before we capture the CO₂. The absence of the Nitrogen included in the atmosphere leads to NO_x by-products being eliminated also.

2.1.4 Physical absorption

Physical absorption of CO₂ is based in Henry's law. There is not any form of altering the chemical identities of either CO₂ or of the solvents. Instead, the breakdown of CO₂ takes place because of the Van der Waals attraction force(Ban, Z.H., et al, 2014). To have better results in this technic we must obtain high pressure and lower temperature, while we need to reverse these conditions(high temperature and low pressure) in the stage of the stripping of the CO₂ from the absorbent, before transportation and storage. Most commonly used absorbents are active carbon, silica membranes and zeolite.

A similar procedure can be used, with chemical absorbents instead of physical ones, such as calcium oxide(CaO) and solid amines sorbents.(Force, C.A.T., 2009)

2.1.5 Membranes

This technology is best suited for eliminating CO₂ from natural gas using the Knudsen diffusion principle and the Fick's molecular diffusion(Khalilpour, R. et al. 2015). It is also considered as the best solution for pre-combustion capture, particularly if the CO₂ has a high partial pressure.

2.2 Transportation of CO2

Following the capture of CO₂ and the separation of it from the means of capture, it must be transported to a location where it is going to be either permanently stored or to a facility where it is going to be used.

For the transportation via pipelines to take place CO₂ is usually in a supercritical stage. That means that the transportation temperature must be 31 degrees Celsius while the pressure must be 73.77 bar. In these conditions CO₂ has a density 500 times larger than when it was a gas(White, C.M., et al. 2005). This way the transportation is made cheaper and can be implemented with both onshore and offshore solutions.

Other means of transportation include specially designed vessels, that can carry the CO₂ at high pressure and low temperature(-2 degrees Celsius and 20 bars respectively).

2.3 Long-term CO2 storage

Long-term storage of CO₂ can take place in different ways depending on the area in which the CO₂ is captured(Aminu, M. D., et al. 2017)

2.3.1 Underground storage in geological formations

Using specific geological formations to store CO₂ is the most accessible and economically sound practice for the isolation of CO₂. The fact that there are six different types of formations in existence that can provide for the long-term storage and isolation of CO₂ makes this practice even more favorable.

These formations include:

- Saline aquifers
- Depleted oil and gas reservoirs
- Unmineable coal seams
- Formations of Basalt
- Hydrate storage of CO₂ below the surface
- CO₂-based enhanced geothermal systems

2.3.2 Deep Ocean storage

This planet's surface is mainly covered by oceans reaching as deep as 11 km in the Mariana Trench and averaging at 3,8km of depth. Oceans naturally store CO₂ from the atmosphere in them.

In fact, they stored about 40% of the CO₂ produced by humans during the industrial period. It has been calculated that if they are introduced with CO₂, they can store it for several hundred years.

However, the legal status of storing CO₂ in the oceans is not clear, since it is not allowed to dispose of industrial waste in the sea, according to the London Convention.

Also, the impact of such disposal to the organisms living in the deep sea and the impact in the water itself causes reasons for further studies.

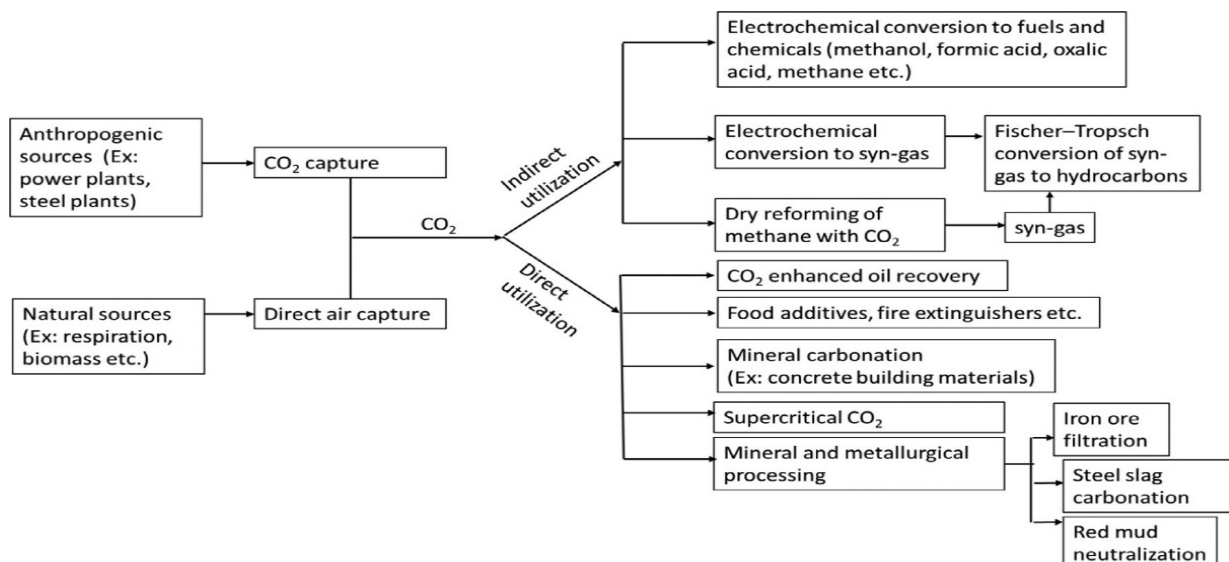
2.3.3 Mineral Carbonation

With this method the CO₂ that has been captured is undergoing a chemical reaction with metal hydroxides or oxides. Stable carbonates are thus produced.

This process can take place in two different ways. One option is on site, where we inject CO₂ into geological formations. The other option is to excavate the rock formations, move them to an industrial plant and introduce the CO₂ there.

2.4 CO₂ utilization

CO₂ capture and long-term storage comes at a cost for the enterprise that decides to abide by the regulations and help fulfill the Paris Agreement.(Zhu, Q., 2019). In that perspective new technologies for the utilization of the captured CO₂ have come into development, instead of long-term storage. This utilization can take shape in the production of ecological fuels that can at least partially replace fossil fuels as the raw materials used. Another use of the captured CO₂ is for the creation of chemicals and even building materials. Obviously to get a different final product, one has to use different processes.



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2.4.1 Fuel production from CO₂

CO₂ can be converted into a number of ecological fuels using electrochemical conversion.

One of the processes used is the creation of SynGas and then the production of synthetic fuels such as gasoline, methane or diesel. The process needs high pressure and temperature to produce long-chain hydrocarbons, using The Fischer-Tropsch process. The upside of this process is that it is exothermic, thus producing vaporized water needed in the initial part of the process.

Recycling part of the energy needed results in an efficiency of 70%, when it comes to the conversion of the electric energy produced by renewable sources, to the heating value of the fuel produced.

Another process involves the alkaline electrolysis of H₂O under pressure to produce H₂ which then reacts with CO₂ and produces e- CH₄ as the final product. The purity of the final product is higher than 96% and has been used by Audi in its e-gas project.

Finally, using electrochemical conversion CH₃OH can be produced and then used as an alternative fuel for transportation.

¹¹ Sriram Valluri, Victor Claremboux, Surendra Kawatra, Opportunities and challenges in CO₂ utilization, Journal of Environmental Sciences, Volume 113,2022,Pages 322-344

2.4.2 CO2 usage in metallurgy

CO2 can be used during the production phases of both iron and steel from iron ore(Valluri, S. et al 2022).

When it comes to steel it can be used for controlling the temperature of molten steel, thus controlling the production of dust.

If CO2 is introduced into steel slag, it will produce carbonated steel slag, a material that is very useful and that can be used as a coarse aggregate or in asphalt. If it is fine carbonated steel slag and not coarse then it can be used in cement mortar. By introducing CO2 into steel slag CO2 will be permanently sequestered. Estimations predict that as much as 268 Mton of CO2 per year can be isolated this way.

Another way to isolate CO2 while helping the environment and potentially creating extra profits is its introduction into the red mud. Red mud is the solid waste that is created when bauxite is turned into alumina. Red mud is very caustic and very difficult to dispose of, thus posing a significant risk for the environment. By introducing CO2 in the red mud, the causticity is neutralized, while CO2 is permanently isolated. If this method is used, it is estimated that 330 Mton of CO2 will be captured while treating the existing red mud, and another 11.6 Mton of CO2 will be needed per year to cover the alumina industry demands. Extra profits might be presented by the further use of red mud after been neutralized. Then it will be possible for the rare earth materials that often exist within it to be extracted.

2.4.3 CO2 enhanced oil recovery

During the recovery of oil from an oil reservoir a technique called advanced oil recovery is used. This technique may use chemical, gas or oil injections into the reservoir and it helps to recover between 30 and 60% of the total oil in the reservoir.

If the gas injection technique is used, then CO2 accounts for about 50% of the gas used.

3. Onboard Carbon Capture and Storage(OCCS)

Out of the before mentioned techniques for capturing CO₂ , in the marine sector three are mainly applicable. Out of them Oxy-fuel and pre-combustion remove carbon from the fuel before the combustion. In order to be used in the shipping industry a complete redesign of the engines of the vessels needs to take place, making them both costly and time-consuming.

Post-combustion¹² uses a technique that captures CO₂ from the gases produced by the combustion process. That means that only minor modifications in the engine design are necessary. This makes it not only less time consuming to install, but also cheaper and thus easier to introduce in the shipping industry. Here it must be mentioned that for this OCCS system to work the vessel must have an EGCS installed also.

What makes the process of OCCS different from the classical CCS techniques is that it is not possible to directly transport the captured CO₂ to a storage facility. The captured CO₂ must be temporarily stored onboard the vessel and then get transferred to the first available onshore facility.

This limitation is significant as the volume of CO₂ that can be stored on board the vessel is limited, and that in turn causes limitations to the functionality of the system, especially when we take into consideration that most global trade routes involve multiple days of sailing.

With the current technology for OCCS to work continuously the vessels need to have frequent approaches to suitable offloading stations for the CO₂. The ships engine of course will not be affected if the OCCS system is taken offline.

Storage of the captured CO₂ can take place in both liquid and gas form, or in other substances, within tanks and supporting systems. Offloading can take place via ship-to-ship transfer, to a suitable feeder vessel, or in the port directly to pre-existing infrastructure, such as pipelines or tanks. Following that the stored CO₂ can be moved to its permanent storage facility.

¹² [https://www.lr.org/en/knowledge/horizons/march-2023/carbon-captures-role-in-maritimes-energy-transition/#:~:text=Carbon%20Capture%20and%20Storage%20\(CCS\)%20systems%20are%20technologies%20that%20can,fossil%20fuels%20in%20power%20generation.](https://www.lr.org/en/knowledge/horizons/march-2023/carbon-captures-role-in-maritimes-energy-transition/#:~:text=Carbon%20Capture%20and%20Storage%20(CCS)%20systems%20are%20technologies%20that%20can,fossil%20fuels%20in%20power%20generation.)

The most important parameters that must be taken into account before a company decides to move forward with the installation of an OCCS system are mentioned below.

3.1 Fuels Used in the shipping industry

According to EMSA the vessels over 500GT that were in service in 2022 were over 68000 and out of them by the end of 2024 only 1860 were capable of using alternative fuels with another 1737 being ordered. That gives a total of 3600 vessels, which is a bit below 5% of the fleet, according to LR¹³.

Table 1 - World fleet: total number of ships, by type and size

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Ship type	Small ⁽¹⁾		Medium ⁽²⁾		Large ⁽³⁾		Very large ⁽⁴⁾		Total	
	Count	%	Count	%	Count	%	Count	%	Count	%
Bulk carriers	279	0.5%	3,901	8.1%	7,103	52.7%	1,937	26.6%	13,220	10.4%
Container ships	19	0.0%	2,409	5.0%	1,684	12.5%	1,624	22.3%	5,736	4.5%
Fishing vessels	20,124	34.5%	5,806	12.1%	4	0.0%	1	0.0%	25,935	20.4%
Gas tankers	34	0.1%	1,182	2.5%	475	3.5%	619	8.5%	2,310	1.8%
General cargo ships	4,105	7.0%	12,181	25.4%	288	2.1%	0	0.0%	16,574	13.1%
Offshore vessels	2,871	4.9%	5,097	10.6%	122	0.9%	319	4.4%	8,409	6.6%
Oil and chemical tankers	1,985	3.4%	7,513	15.7%	2,827	21.0%	2,291	31.4%	14,616	11.5%
Other tankers	448	0.8%	776	1.6%	16	0.1%	0	0.0%	1,240	1.0%
Passenger ships	4,417	7.6%	2,945	6.1%	299	2.2%	205	2.8%	7,866	6.2%
Ro-ro cargo ships	1,025	1.8%	1,111	2.3%	553	4.1%	277	3.8%	2,966	2.3%
Service ships	3,801	6.5%	3,810	7.9%	38	0.3%	8	0.1%	7,657	6.0%
Specialized cargo ships	8	0.0%	287	0.6%	63	0.5%	9	0.1%	367	0.3%
Tugs	19,131	32.8%	920	1.9%	0	0.0%	0	0.0%	20,051	15.8%
Total	58,247	100%	47,938	100%	13,472	100%	7,290	100%	126,947	100%

Source: Equasis ⁽¹⁾ GT<500 - ⁽²⁾ 500≤GT<25,000 - ⁽³⁾ 25,000≤GT<60,000 - ⁽⁴⁾ GT≥60,000

This means that the majority of the merchant fleet is still using either HFO with the usage of EGCS when needed, or LSFO if the vessel does not have EGCS. And it will be using these fuels in the existing fleet till these vessels complete their life cycle and get recycled.

This is a problem since Marine Heavy Oil has one of the highest fuel

Type of Fuel	Carbon Content (m/m)	Fuel Coefficient (c _F) (kg CO ₂ /kg of Fuel) ¹
Marine gas oil	0.875	3.206
Marine diesel oil	0.875	3.206
Light fuel oil	0.86	3.151
Marine heavy oil	0.85	3.112
Methane	0.75	2.750
Propane	0.819	3.000
Butane	0.827	3.030
Propylene	0.857	3.141
Biodiesel	0.86	3.151
Methanol	0.375	1.375
Ethanol	0.522	1.913
Dimethyl ether	0.522	1.913
Ammonia	0	0

¹ Sometimes, the carbon dioxide emission coefficient is shown using the units kg CO₂/MJ or kg CO₂/kWh, where the lower heating value of is taken into consideration.

coefficients of all possible types of marine fuels(Herdzik, Jerzy. 2021).

The usage of HFO in the majority of the shipping industry makes the usage of OCCS systems a necessity if the industry wants to abide with the IMO regulations for reductions of CO₂ emissions, till alternative types of fuels are used extensively.

In this research the type of fuel used by vessels to both achieve compliance with MARPOL Annex VI and the reduction of CO₂ through OCCS technology will be HFO which is cheaper than LSFO and thus providing some economic benefits to the company.

3.2 Onboard storage facilities

When we are talking about OCCS system we must keep in mind that the storage of CO₂ will not be permanent(Ahmed, Y.A et al. 2025). The stored gas will need to be offloaded every time the vessel approaches a port or a facility that will be able to accept CO₂.

Depending on several parameters, including the CO₂ capture rate, the size of the storage facilities and the voyage each vessel will undertake, the crew will have to make calculations to make sure that the storage capacity onboard will not be excited before the next suitable port.

The time needed for the offloading of CO₂ is also critical as this needs to take place as fast as possible for the vessel to be able to proceed with the rest of its operations, or to proceed with its voyage to the destination.

There are four types of temporary storage of CO₂ onboard vessels

3.2.1 Gaseous phase Storage

The storage of CO₂ in its gaseous state is something that is not considered practical because the space required to be occupied by the containment tanks is more than the space available onboard vessels, especially if we are talking about retrofits.

However, it is feasible under very specific circumstances, such as very small travel, the vessels layout in general and of course the vessels requirements in both cost and energy.

3.2.2 Supercritical phase Storage

The storage of CO₂ in its supercritical fluid phase means that CO₂ will be stored at above 73 bars and at 31,1 °C .

In this state CO₂ is being transferred through pipelines but storage in these conditions has a higher cost than in its simple liquid form, since CO₂ has a triple point of 5.18 bar and 56.6 °C.

3.2.3 Liquid phase Storage

Storing CO₂ in its liquid form has its advantages in comparison to other storing methods. First, the offloading process from the vessel is easier, since CO₂ as a liquid can be easily handled by pumps. Apart from that, because of the liquid form, the density of CO₂ is higher than in its gaseous phase, resulting in higher volumes being stored in the same space.

The size of these storage facilities may differ, depending mainly on the size of the vessel, but also on the type of the vessel and of course the area in which this vessel is operating.

Liquid storage technology is the technology that is used in this study.

3.2.4 Solid phase Storage

The fourth type of storage is the solid phase. There are two distinct methods to store CO₂ in a solid phase.

The first is to solidify the gas itself by lowering the temperature to -78 °C. In this temperature the installed system can be operated in atmospheric pressure. But apart from the energy necessary to drop the temperature to -78 °C there is an extra requirement of 573 kJ per kilogram of CO₂, for the solidification to be initiated. This means that this process will require a lot of energy increasing the operational cost of the system.

The second method involves a chemical process that will bind the extracted gas to another substance. This process is not yet applicable for widespread use but is under development in experimental conditions.

3.3 Deviation from destination

The limitations set in the storage capacity of each vessel will determine the rate with which each vessel will have to offload the captured CO₂ and that means that there will be cases during a voyage that the vessel will have to deviate by its set course to offload CO₂.

To this date any deviation from course is considered as days off hire and it is excluded from the days that a shipping company will get paid from the charterer, unless explicitly stated in the contract.

In this study we will consider that in the future such a cost might be included in the charter party since it might be in the charterer's best interest to capture the CO₂ even if the ship has a delay in its arrival at its destination, than not capturing the CO₂. And we will see how this cost might affect the overall cost-benefit of this installation.

4 Methodology

In this research we will try to present a cost-benefit analysis of an OCCS system in order to calculate both the economic savings that a company will have by the installation but also the costs associated with such a project.

To create this cost benefit analysis of the OCCS we had to proceed with some assumptions that need to be implemented before this system can be used globally.

The main assumption is that there will be a storage facility in all the major ports where the captured CO₂ can be offloaded and that the vessel will be using HFO with an Exhaust Gas Cleaning System(EGCS) fitted.

We assume that depending on the size of the vessel, the larger vessels will have the capacity to store up to 500 tons of CO₂ and the smaller vessels up to 300 tons. This storage capacity is suggested by SINOTECH, the company that provides all the primary technical data of the OCCS system after interviews.

Another assumption is that the vessels will be transporting goods for 80% of the year. Since the time enroute depends highly on the type of vessel and the route that this vessel

will undertake, for this assumption we will use as an example the container vessels(Durmusoglu, et al., 2015) ¹⁵.

Also, since each vessel, depending on the kind of engine it has on board and other factors such as age, weather conditions, hull and propeller condition, has a different consumption we have taken the average consumption of the vessel category¹⁶.

The above assumptions allow the calculation per year of the CO₂ emitted from each vessel category since the Tank-to-Wake(TtW) emission factor for HFO is 3.114 g CO₂/g of fuel.

For the daily hire rate, we used one source for the tankers, and namely the charter rate provided by Navios Maritime Partners on their online page¹⁷, while for the bulkers we used the median of the different shipping routes as they are provided by handybulk.com ship charter rated¹⁸ on the 10th of April 2025.

For the spread between the price of HFO and LSFO we have found that it is not stable as a price. So, we took the spread at the time of the research that was at 96\$ per ton.

When it comes to the system installation cost and maintenance cost, and the OPEX of the system, we have received the primary data from SINOTECH¹⁹ also.

To calculate the savings from the OCCS on board a vessel, if the 2-tier levy is adopted, we need to first calculate the penalty that the vessels will pay annually starting in 2028. So, since HFO has a heat value of approximately 40GJ per ton and an emission factor of 91 gCO₂e/MJ, which is below the 93,3 gCO₂e/MJ that is set as the 2008 baseline, we can go forward with the following calculation.

If we multiply the annual consumption of a vessel, with the heat value and with the emission factor minus the target set and then multiply the result with the price set we will get the annual price a vessel will pay if it uses HFO and takes no actions to reduce the CO₂ emissions.

¹⁵ Durmusoglu, Yalcin & Koçak, Gazi & Deniz, Cengiz & Zincir, Burak. (2015). Energy Efficiency Analysis of Pump Systems in A Ship Power Plant and A Case Study of A Container Ship. P.60 Table 5

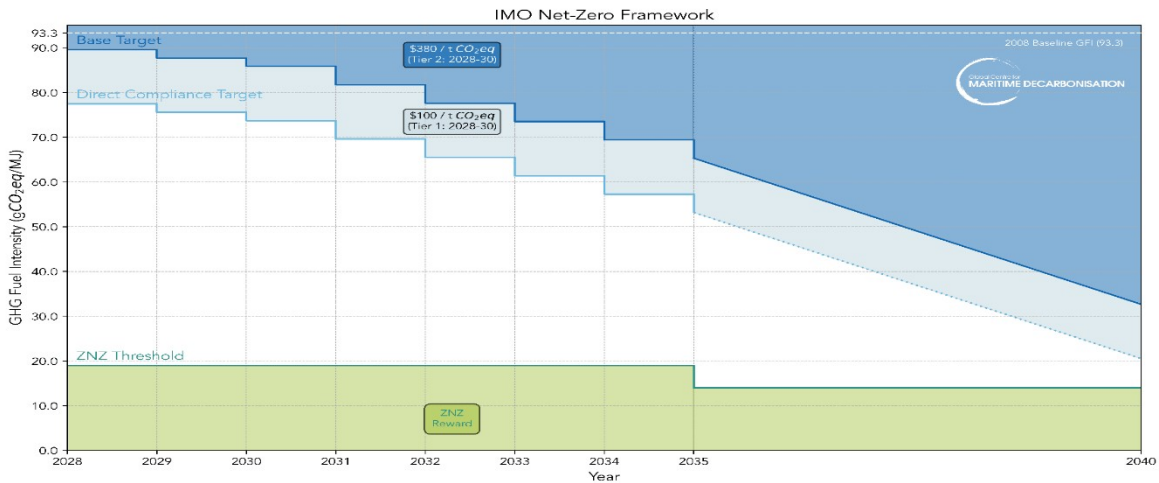
¹⁶ <https://www.shipuniverse.com/big-5-breakdown-size-fuel-burn-and-carrying-capacity/>

¹⁷ <https://www.navios-mlp.com/fleet/>

¹⁸ <https://www.handybulk.com/ship-charter-rates/>

¹⁹ <http://www.sinotechm.com/en/product?catalog=carbon>

To have everything on the same scale we will have the following result when we are talking about the base target. $(\text{Ton/year}) * 40(\text{MJ/ton}) * 103 * (91-y) * (\text{gCO}_2\text{e/MJ}) * \text{tonCO}_2\text{e}/106\text{gCO}_2\text{e} * 380(\$/\text{tonCO}_2\text{e}) = x \text{ \$/year}$. Where with y we have the base target set by IMO since it varies from year to year. The same principle can be applied to the direct target by replacing $(91-y)$ with the number difference between the base and the direct target and by adjusting the price of the levy to 100 $\$/\text{ton}$.



Knowing the penalty and the reduction percentage of CO₂ emissions required per annum we can calculate the savings a company will have by installing an OCCS system simply by adding the money not paid to IMO because of the reduction. So, for example if we have a 22% reduction we can see that since HFO has an emissions factor of 91 and we have a 22%, that the new factor is about 71 so by using the table below we can see that up till year 2033 the vessel will not have to pay any direct target penalty and from then on it will only pay partially. At the same time, since it meets the direct target goals up till 2030. So up till then it will not pay any penalty either and after that date it will pay a partial penalty. By using this example, we can see that for this vessel the amount of CO₂ reduced surpasses even the direct target for the first three years. During these years we can calculate using the above formula the extra credits that can either be used at another vessel of the same company, on the same vessel at a later time, or can be sold to another company for a profit. Since this price is not set, we will use as a base line the same amount stipulated by IMO for the direct target of 100\$.

Year	Basic target deduction %	Basic target	Direct target deduction %	Direct target
2028	4	89,6	17	77,4
2029	6	87,7	19	75,6
2030	8	85,8	21	73,7
2031	12	81,7	25	69,6
2032	17	77,6	30	65,5
2033	21	73,5	34	61,4
2034	26	69,4	39	57,3
2035	30	65,3	43	53,2

Finally, and since we have all the financial factors calculated per year, we can see the annual cost/benefit per category and calculate the ROI of each assumed scenario.

It needs to be mentioned that the EU ETS is not considered in this research, since it is a levy to be paid only for vessels that travel to Europe and not globally, while this research focuses on global trade.

5. Cost benefit analysis

Although the shipping industry has many sectors, this cost benefit analysis will focus on the dry bulk and the wet bulk section.

In this analysis we will take under consideration the parameters that might affect a shipowner's decision in installing an OCCS system, such as the cost of installation, the maintenance cost of the system, the OPEX of the system and the deviation cost but also the savings created by using HFO instead of VLFO.

Because of the limitations in storage capacity that exist due to the storage facilities onboard a vessel this analysis will consider that depending on the size of the vessel it can have, either a 300-ton storage capacity for smaller vessels, or a 500-ton storage capacity for larger vessels.

This capacity will lead to a need to offload the stored CO₂ anywhere between 8 and 20 days, depending on the rate of capture but the vessel size also. That means that the research will presume that every major port along the routes will have the potential to accept the CO₂ from the vessel and then forward it to either the storage facility or the utilization facility.

We will also take into consideration the fact that CO₂ might either be sold when it is offloaded thus causing extra income to the vessel, or the company might have to pay for the CO₂ to be removed.

The fact that in the next MEPC in October 2025 the two-tier levy might be accepted by IMO will also be taken into account and this analysis will try to see how it is going to affect the cost-benefit aspect of such an installation.

5.1 Cost-Benefit Analysis for Bulker

First, this study will focus on how several variables, such as the deviation cost and the price that an owner will either sell or pay for the CO₂ to be removed from a vessel will affect the ROI both with and without the proposed 2-tier levy in the Bulkera sector.

5.1.1 Cost-Benefit Analysis for Bulkiers with no levy

The first step will be to study how deviation cost and the CO2 market will affect the ROI in the bulker section if the 2-tier levy is not implemented.

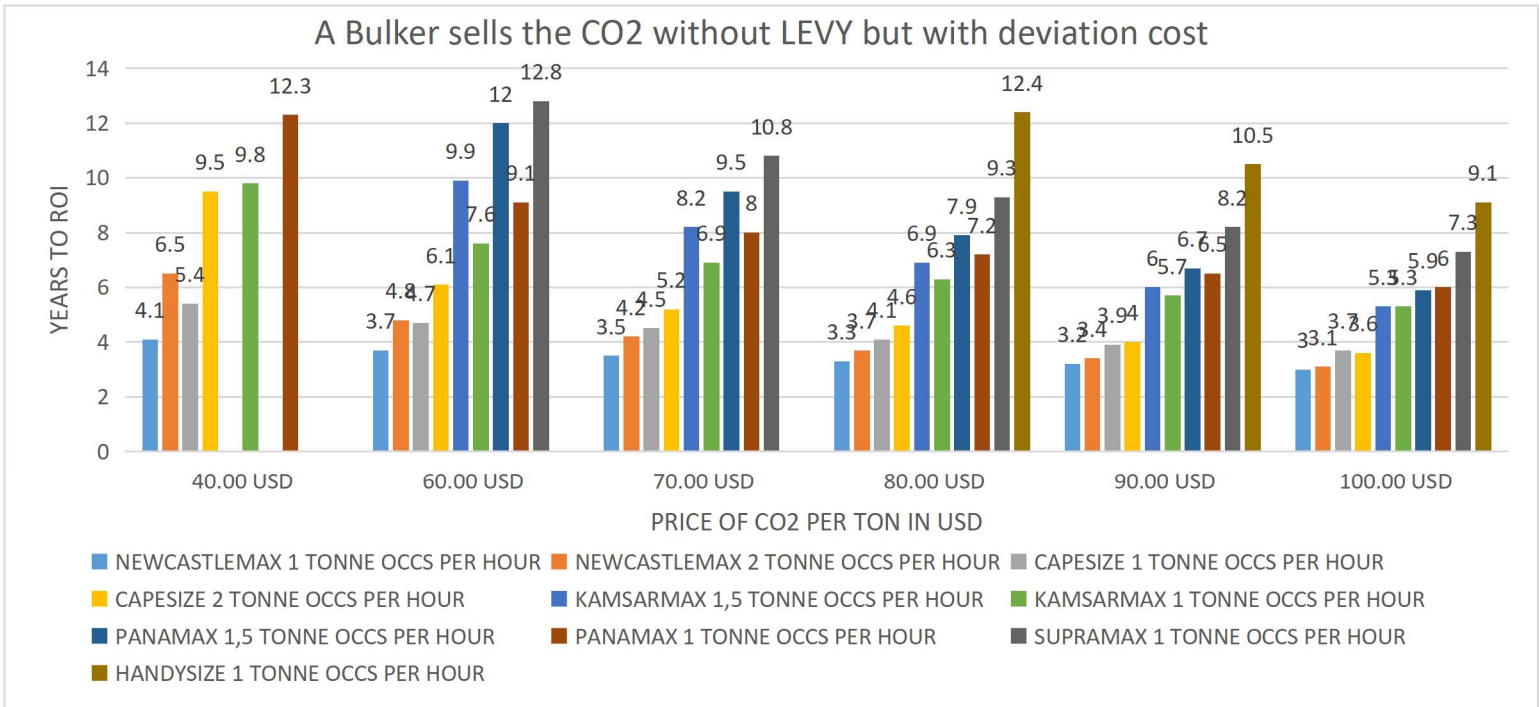


Table 1 A Bulker sells the CO2 without LEVY but with deviation cost

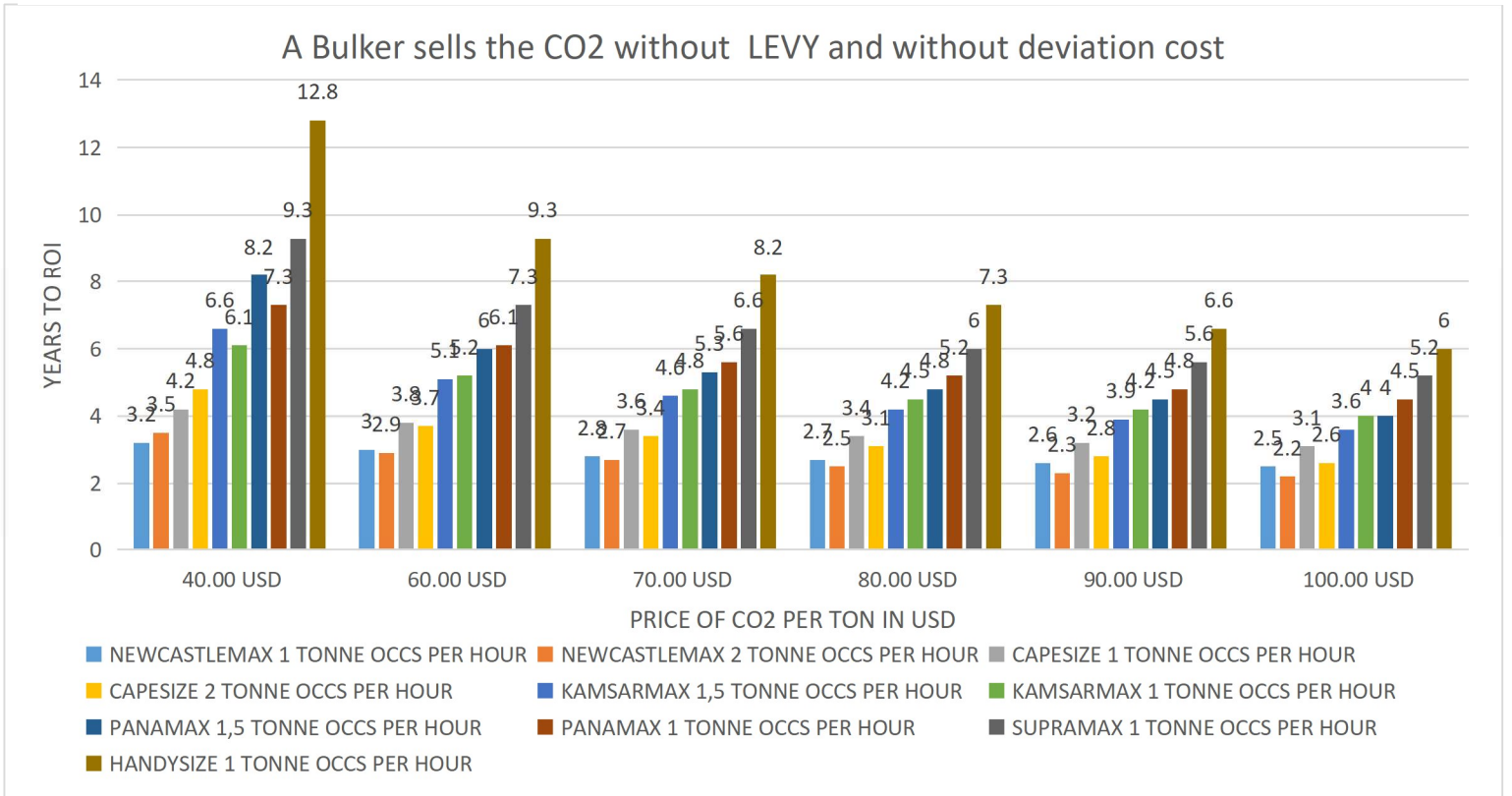


Table 2 A Bulker sells the CO2 without LEVY but without deviation cost

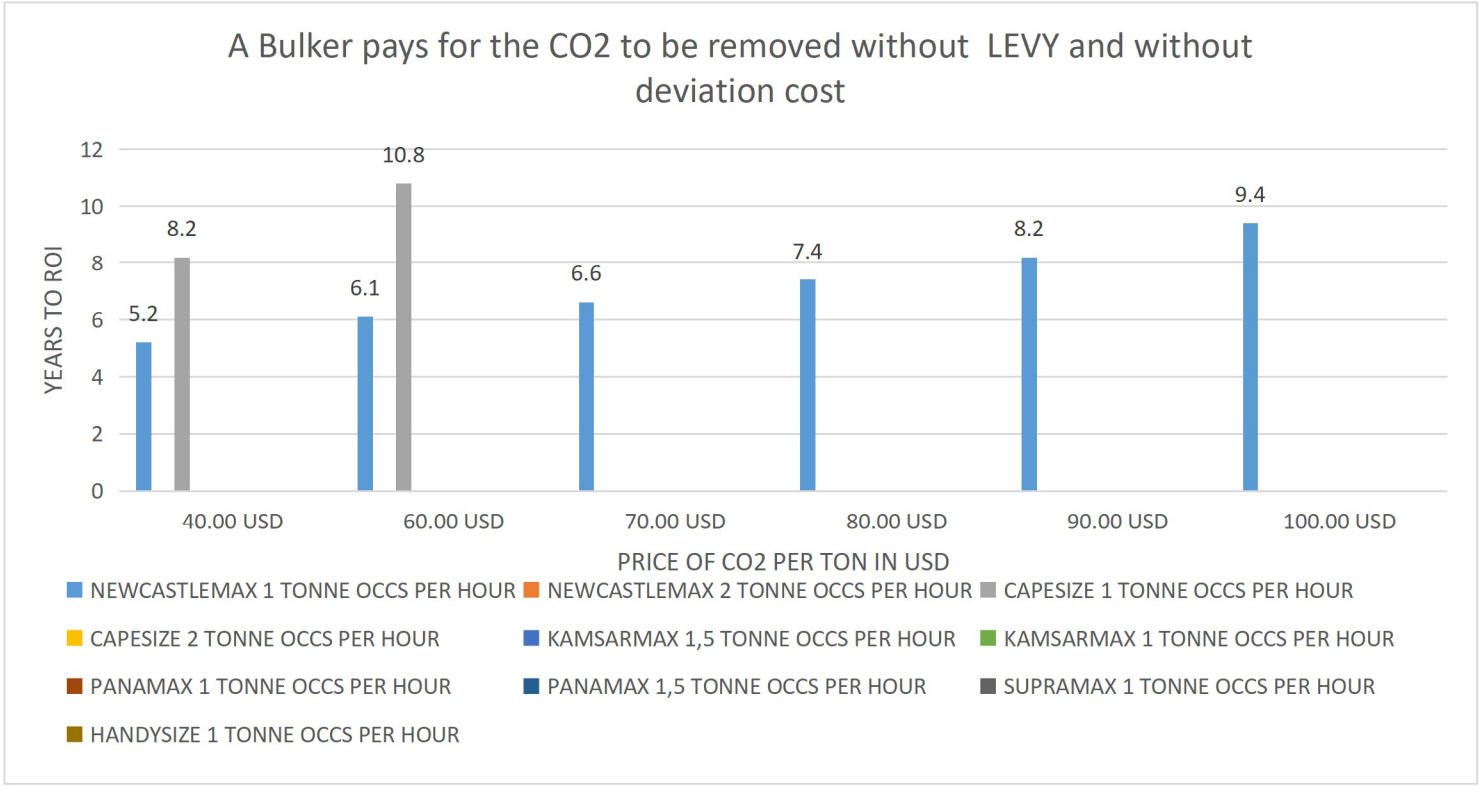


Table 3 A Bulker pays for the CO2 to be removed without LEVY but with deviation cost

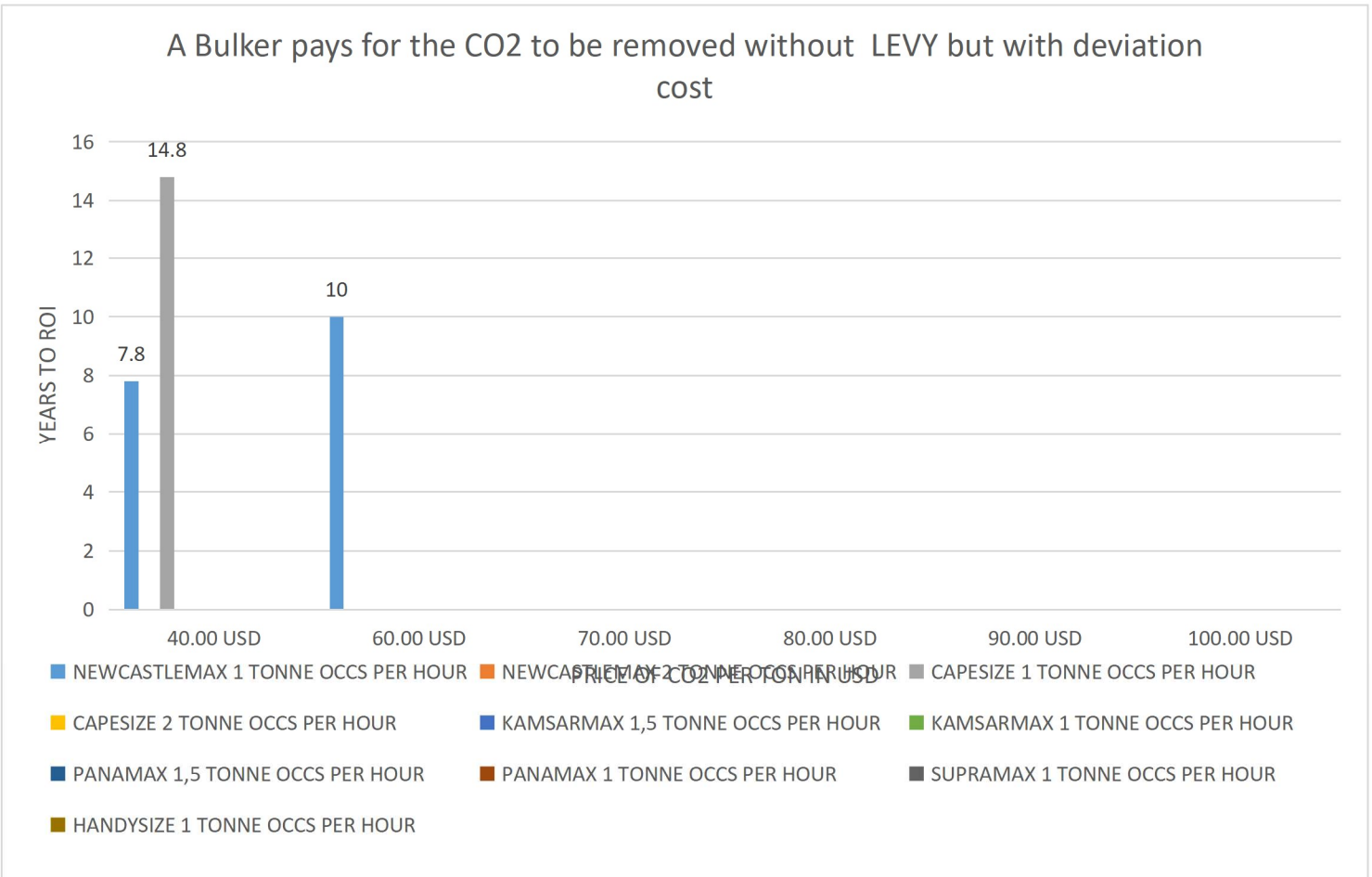


Table 4 A Bulker pays for the CO2 to be removed without LEVY but with deviation cost

From the above four diagrams it is made obvious that even though the deviation cost can create a significant impression on the overall ROI decreasing it up to 30%, if it is not implemented, the main factor that will determine whether the installation of an OCCS system is a sound investment for a shipowner is the CO2 market and specifically the usage of the CO2 after its removal from the vessel.

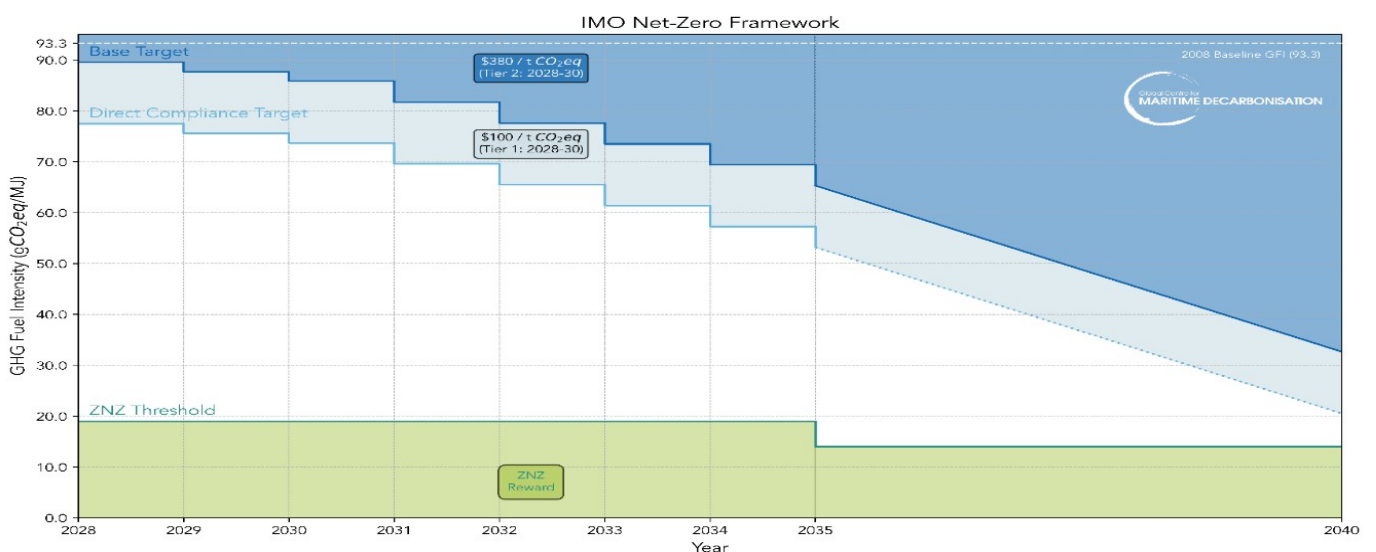
As it becomes obvious, without the existence of the 2-tier levy, if the CO2 is not used as a resource, but is removed for long term storage, then the vessel will have to pay for the removal thus making this investment not a sound one.

There is the exemption of the Newcastlemax category, where for a rate of capture of 1 ton per hour, even if the vessel pays for the removal of the CO2, the ROI remains below 10 years, so for younger vessels it will make sense, especially if the company wants to take into consideration more factors such as an eco-friendly profile.

5.1.2 Cost-Benefit Analysis for Bulkiers with levy

Proceeding we shall make the same comparisons as previously, but this time will take the 2-tier levy proposed by IMO into account.

If the 2-tier levy is adopted in October that will mean that the owners will have to pay a substantial amount of money if they do not meet the required reductions in CO2 emissions. The reduction in CO2 emissions as shown in the table below is the basis for our calculations on the savings created by the CO2 capture



depending on the vessel that we will be studying as well as the capture rate.

A Bulker sells the CO2 with 2-tier levy but without deviation cost

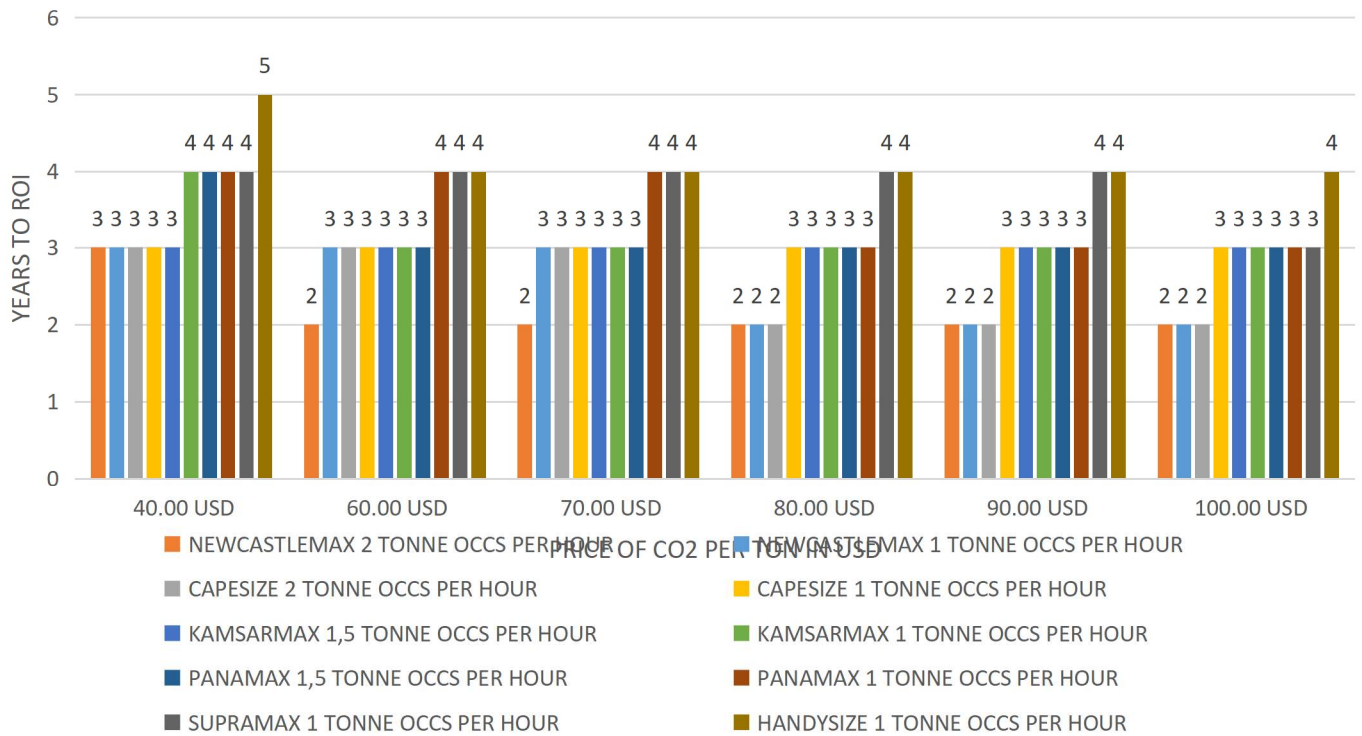


Table 5 A Bulker sells the CO2 with 2-tier levy but without deviation cost

A Bulker sells the CO2 with 2-tier levy and deviation cost

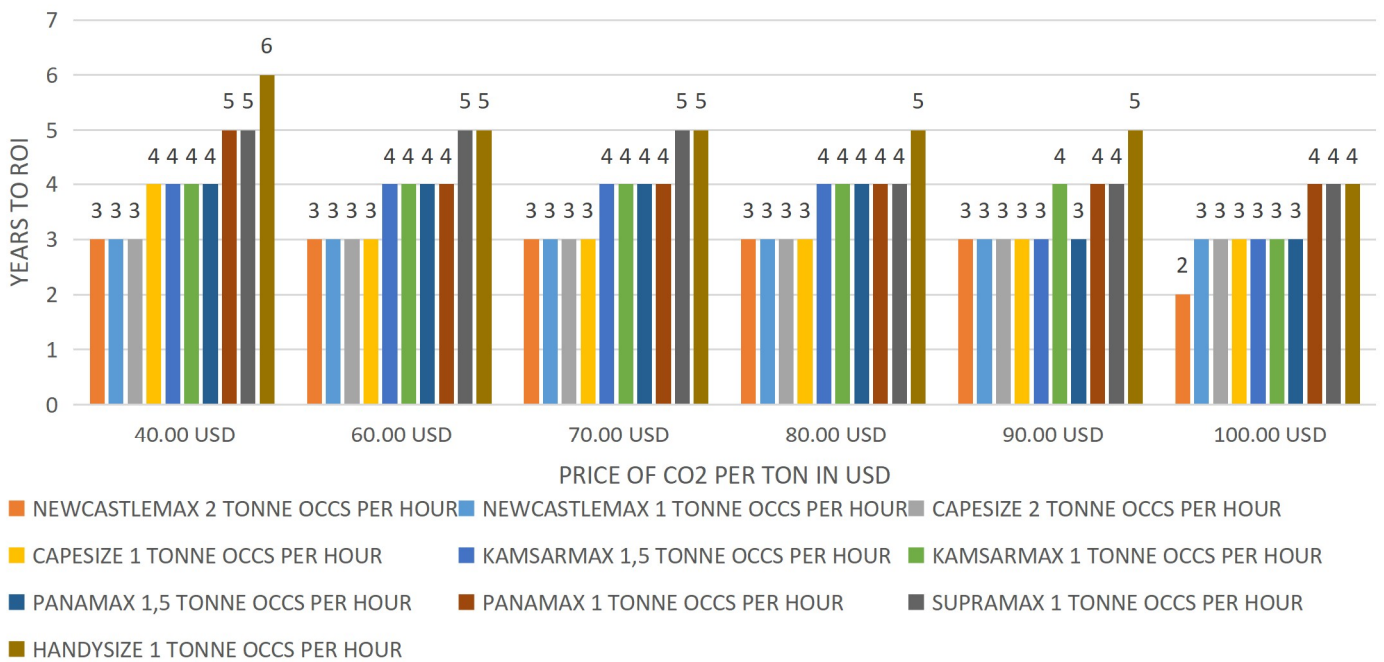


Table 6 A Bulker sells the CO2 with 2-tier levy and deviation cost

A Bulker pays for CO2 to be removed with 2-tier levy and with deviation cost

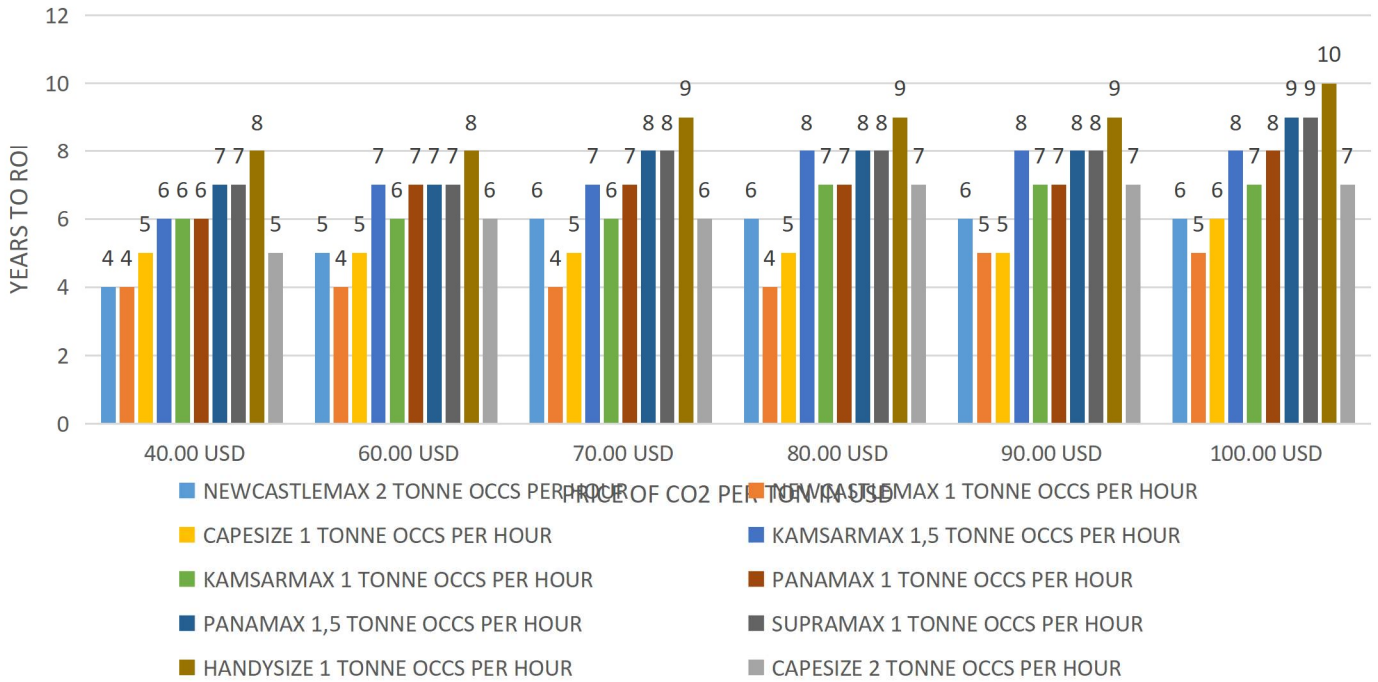


Table 7 A bulker pays for CO2 to be removed with 2-tier levy and with deviation cost

A Bulker pays for the CO2 to be removed with 2-tier levy but without deviation cost

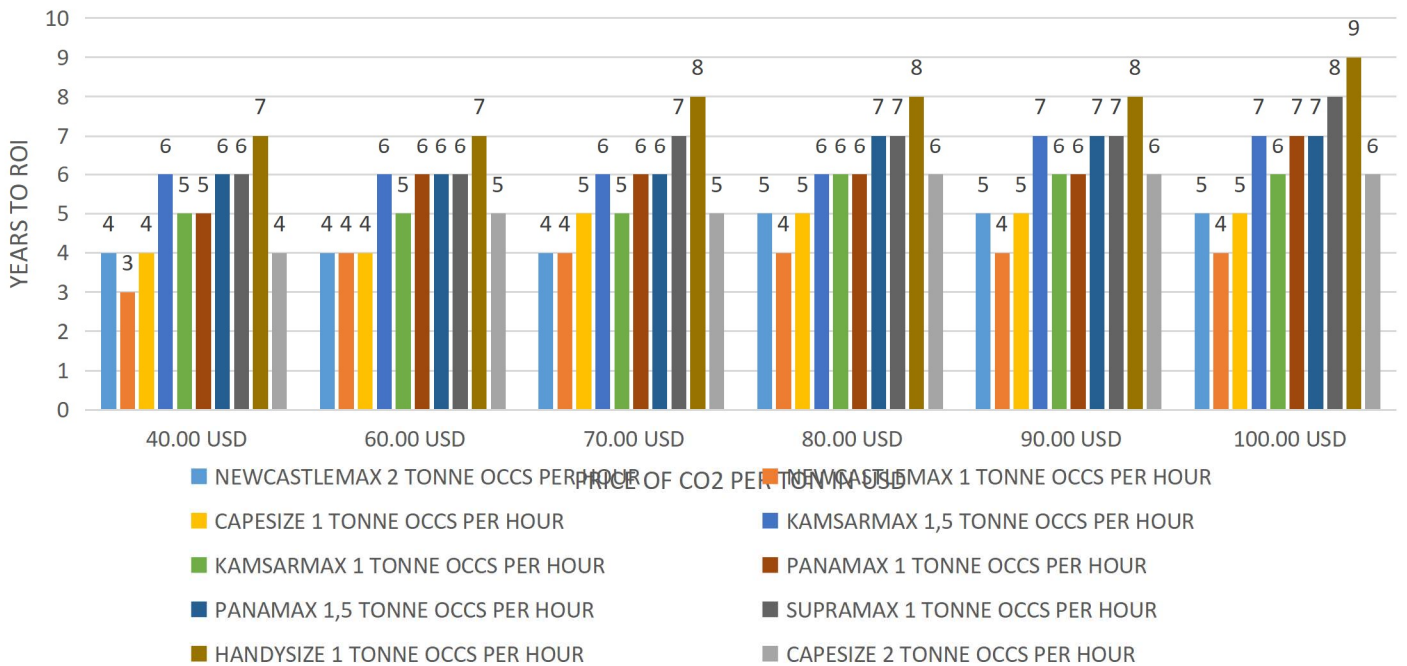


Table 8 A Bulker pays for the CO2 to be removed with 2-tier levy but without deviation cost

As it becomes obvious from the above graphs the implementation of the 2-tier levy is going to have significant implications in the cost-benefit ratio of the installation of the OCCS system onboard vessels.

Even in the worst case scenario of this simulation, when the vessel has to pay 100\$ per ton for the removal of the CO₂ and it also has to be burden with the existence of the deviation cost, the ROI remains below 10 years for all categories of vessels making it a sound investment for ships up to 10 years old and in most cases even older.

5.1.3 Conclusion for the Bulker section

According to the above the conclusions can be separated into 2 different categories.

A. Without the 2-tier levy the market of the CO₂ will play a significant role in the decision of the shipowner about whether it is a sound investment or not to install the OCCS system, since the ROI if the vessel must pay for the CO₂ removal, exceeds 10 years in almost all cases. So, a strong agreement with a suitable buyer must be made before the installation. The deviation cost is also something that must be taken into consideration as its existence will prolong the ROI period substantially.

B. With the 2-tier levy implemented the installation of such a system, especially in vessels under 10 years old, will provide significant benefits in the long run as depending on the type of vessel and the market of the CO₂ the ROI might be as low as 2 years, which means that the vessel will receive significant benefits from this system. The deviation cost will again play a role but a very limited one this time.

5.2 Cost Benefit analysis for Tankers

Following the cost benefit analysis of the Bulkers section this research will do the same in the Tankers section to spot if there are any differences between the 2 of them and to see if the OCCS system can provide a solution that will make sense financially in this section.

5.2.1 Cost-Benefit Analysis for tankers with no levy implemented

Much like in the bulker section, the analysis will begin with how the deviation cost, and the CO2 market are going to affect the ROI in the tanker section if the 2-tier levy is not implemented.

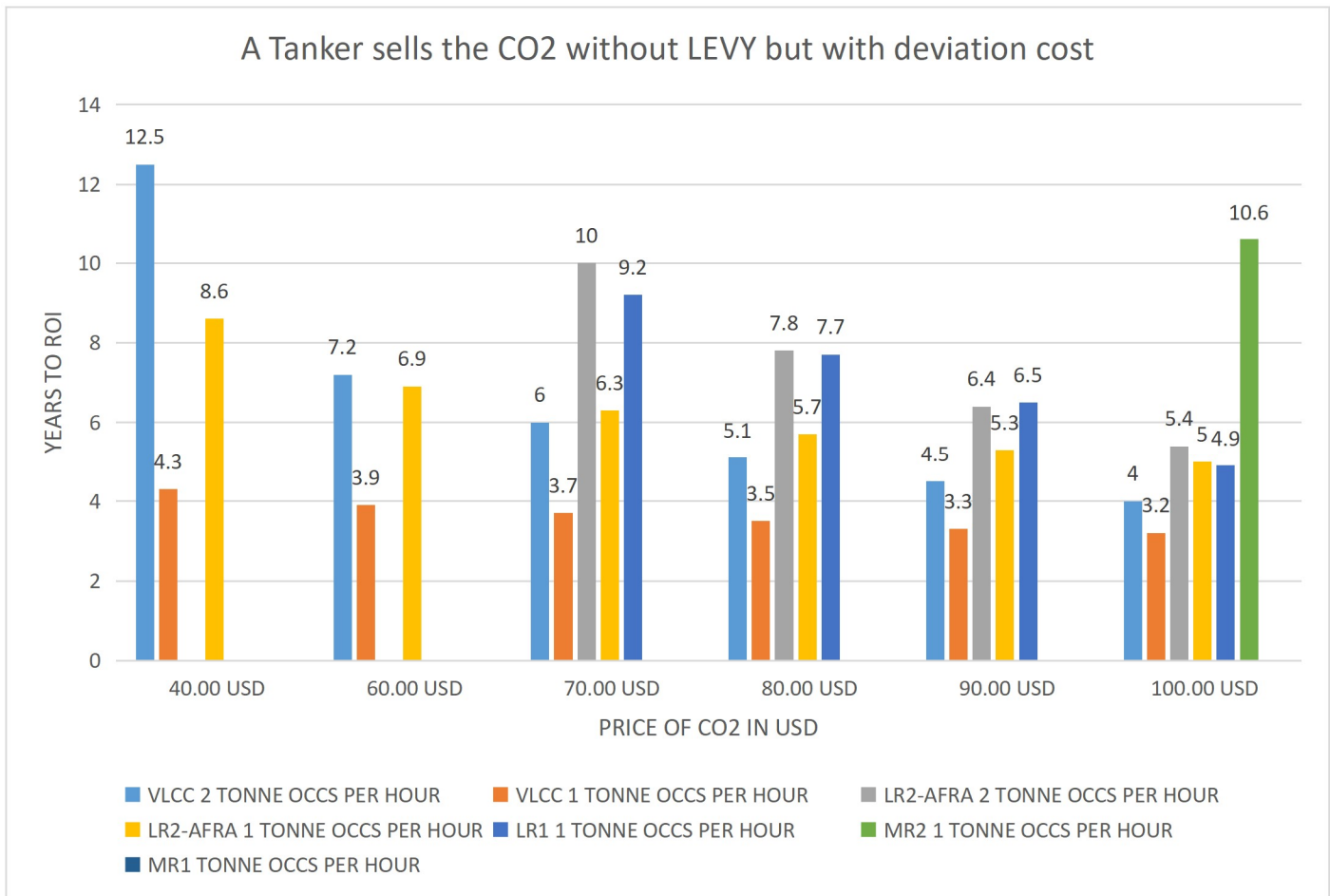


Table 9 A Tanker sells the CO2 without LEVY but with deviation cost

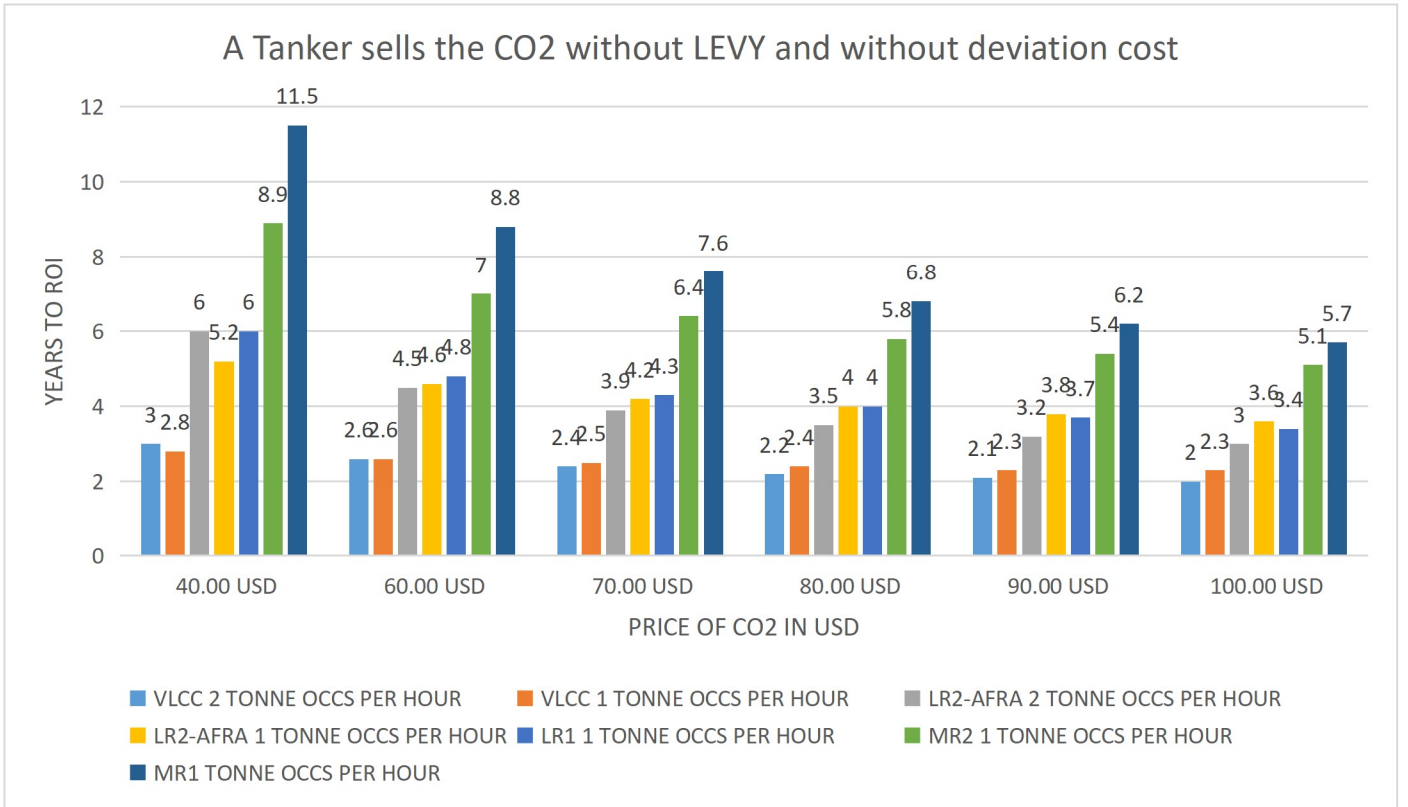


Table 10 A Tanker sells the CO2 without LEVY and without deviation cost

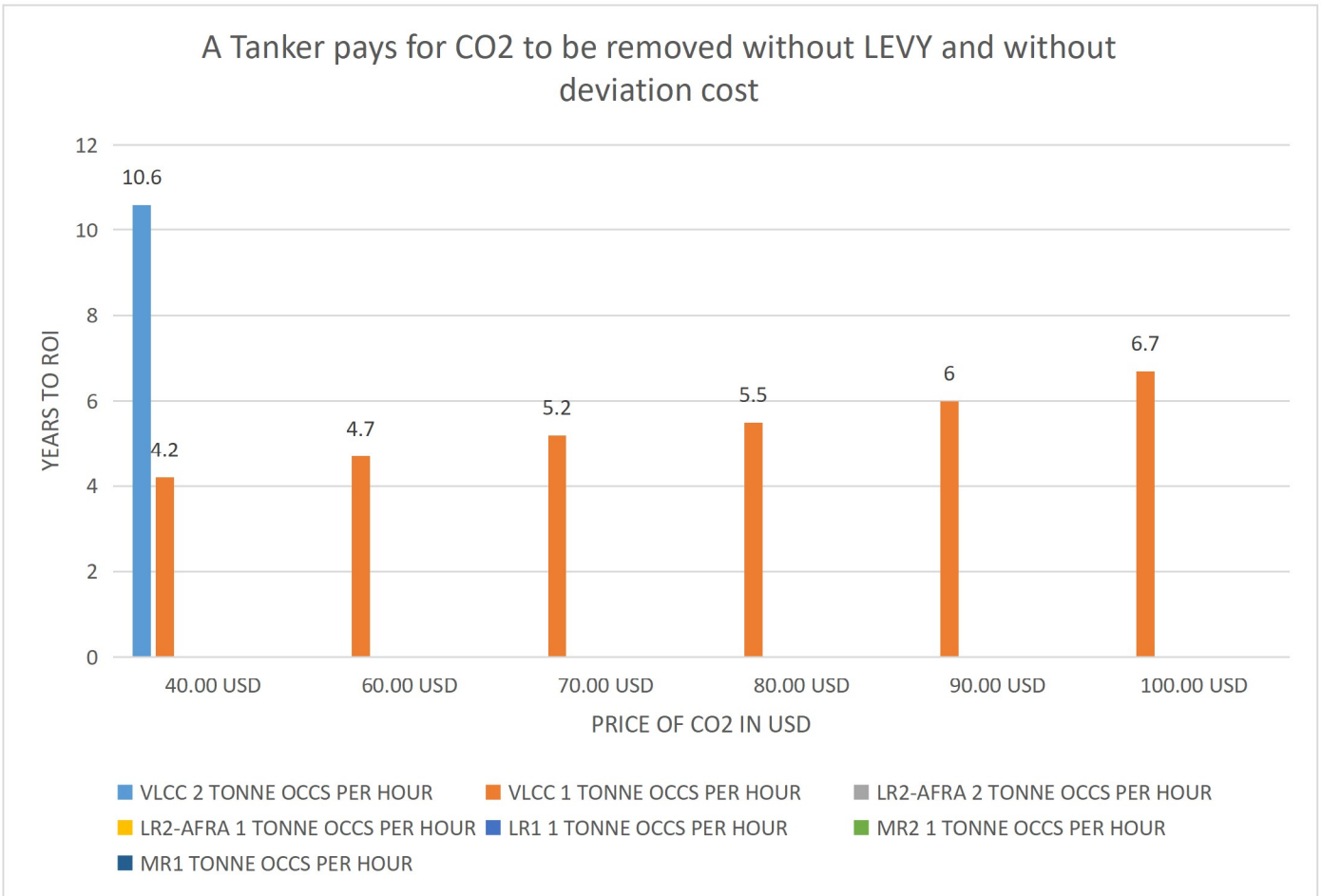


Table 11 A Tanker pays for CO2 to be removed without LEVY and without deviation cost



Table 12 A Tanker pays for CO2 to be removed without LEVY and with deviation cost

By examining the above four graphs it becomes clear that much like in the bulker section, if the 2-tier levy is not implemented the CO2 market remains a very important aspect of the ROI however due to the day rates of the tanker market that are almost twice as high as the rates of the bulker section in this analysis the deviation cost takes a significantly larger part on the owners decision.

Again, if the CO2 is not sold this investment is not a sound one, but this time selling the CO2 is not enough in most of the vessel's categories. The shipowner must come to an agreement with the shipper for the deviation cost if the investment is to be a sound one.

If such an agreement is made then in the case of the VLCC, with a rate of capturing CO2 of 1 ton per hour, the investment is a sound one even if the vessel pays for the removal of the CO2.

5.2.2 Cost-Benefit Analysis for Tankers with 2-tier levy implemented

In the same way that this analysis checked what will happen If the 2-tier levy is implemented in the bulker section, it will follow the same logic to see how it will affect the tanker section.

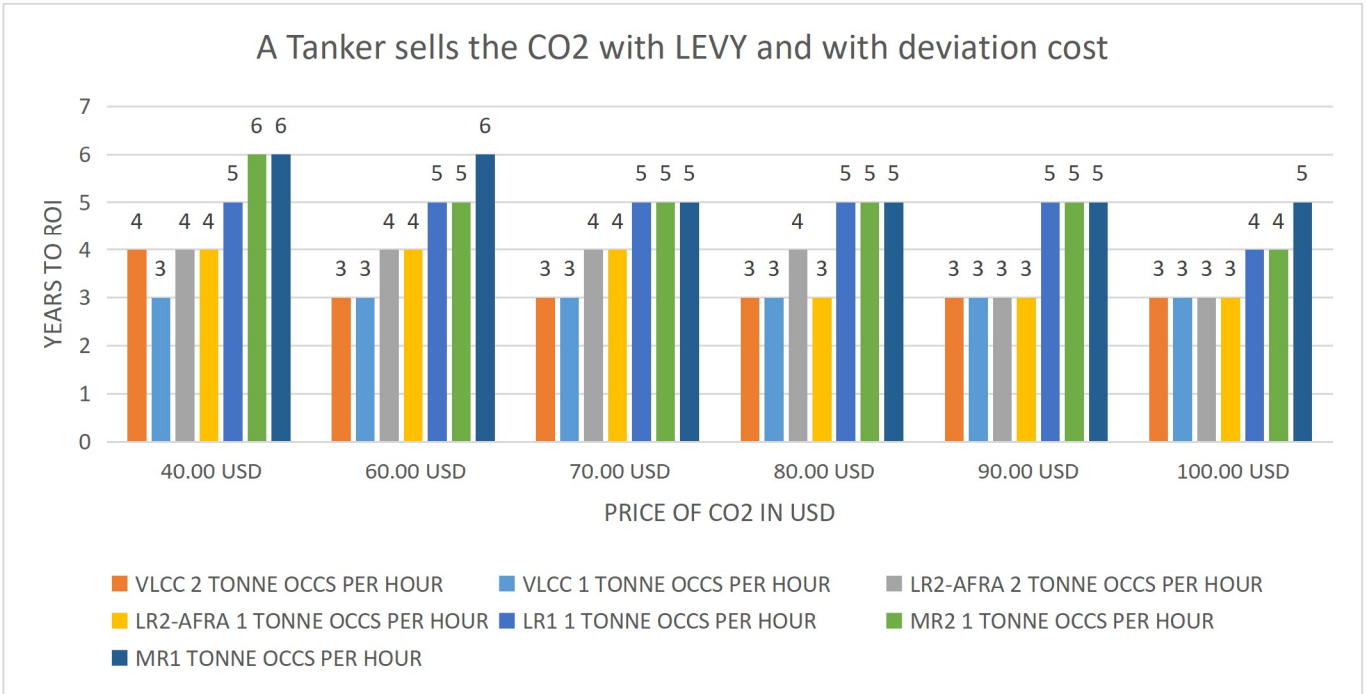


Table 13 A Tanker sells the CO2 with LEVY and with deviation cost

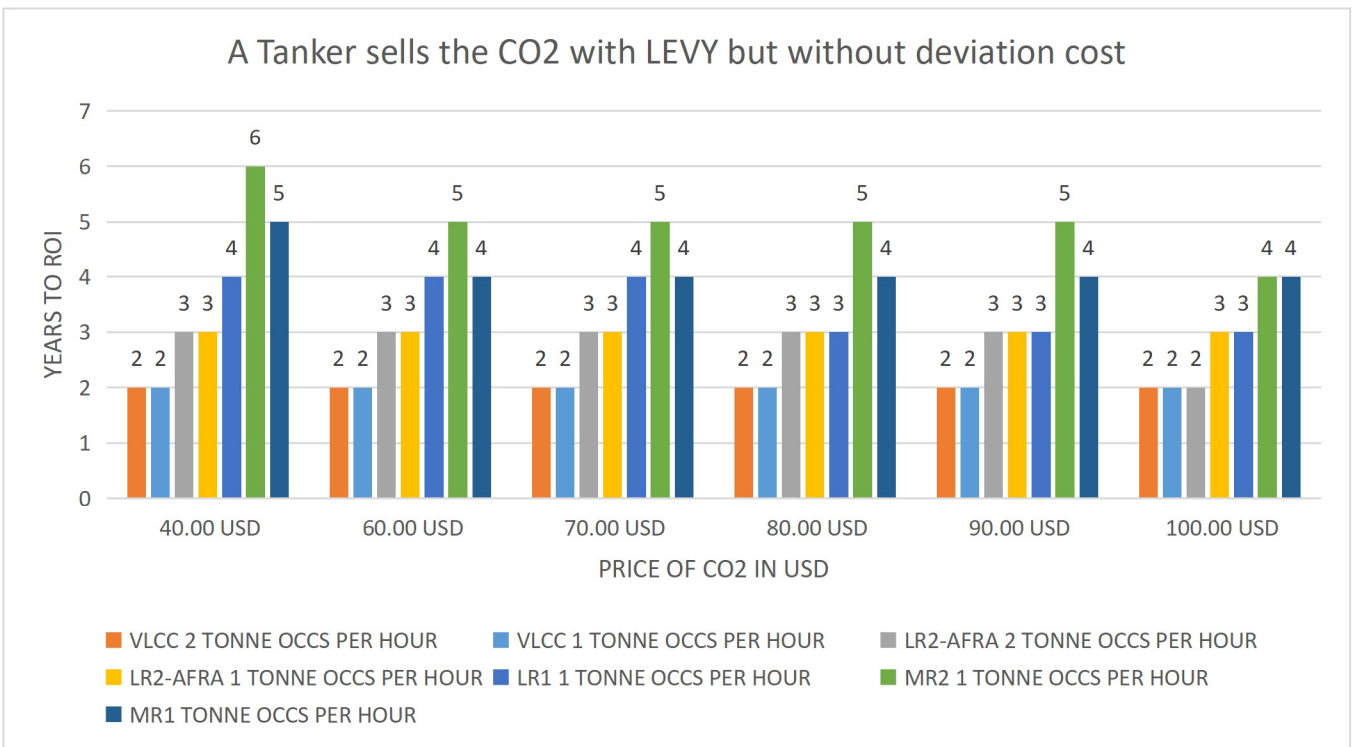


Table 14 A Tanker sells the CO2 with LEVY but without deviation cost

A Tanker pays for CO2 to be removed with LEVY and with deviation cost

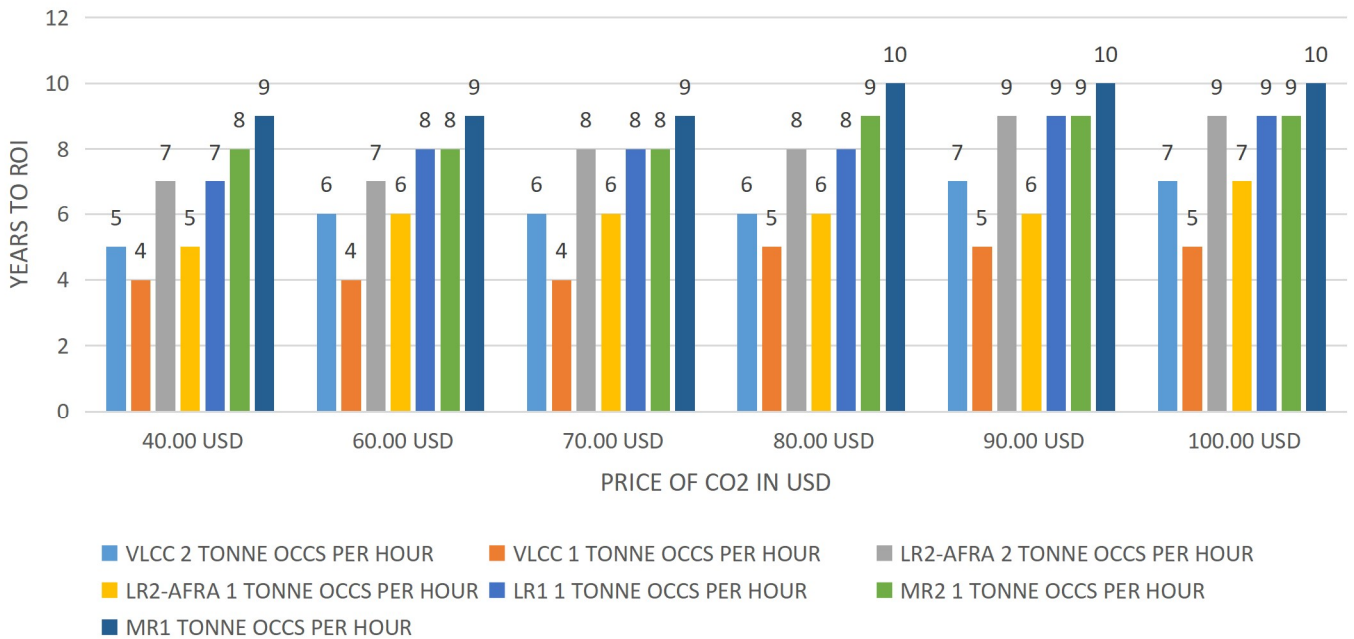


Table 15 A Tanker pays for CO2 to be removed with LEVY and with deviation cost

A Tanker pays for the CO2 to be removed with LEVY but without deviation cost

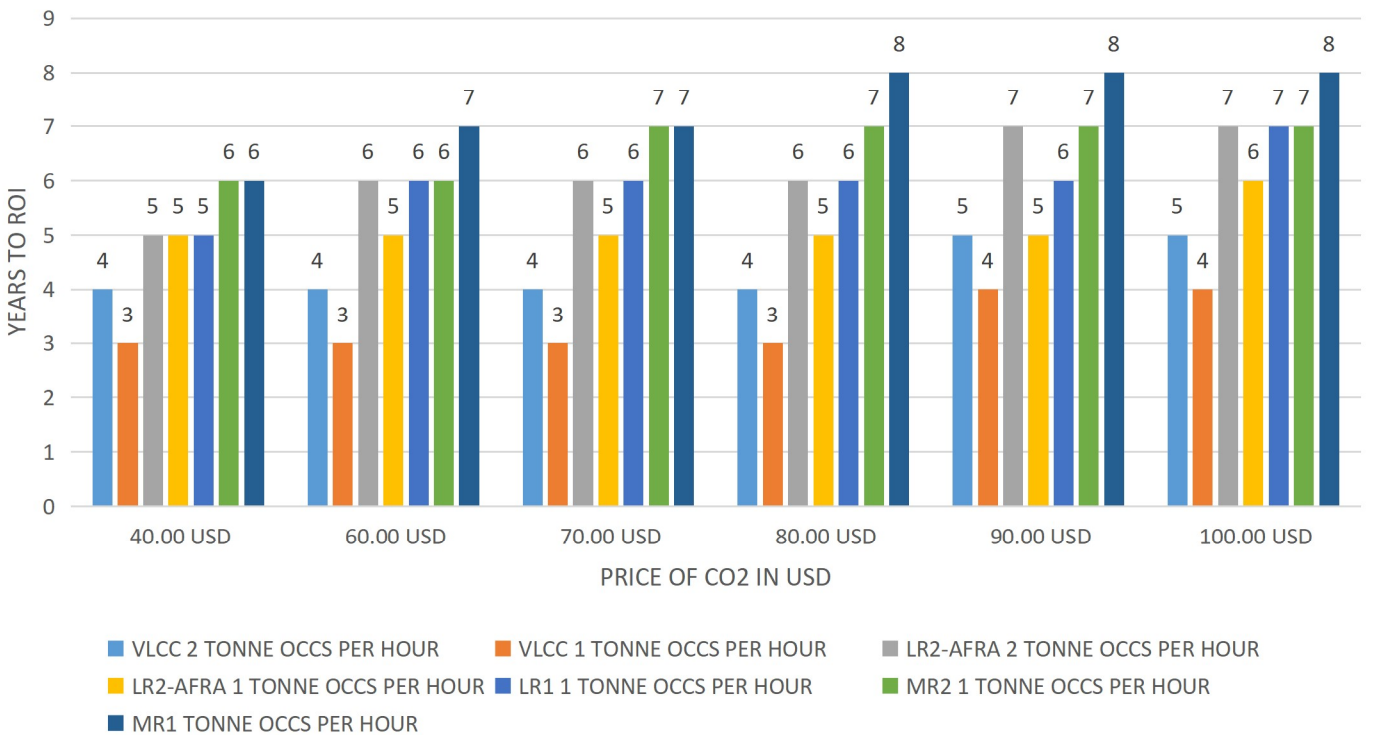


Table 16 A Tanker pays for the CO2 to be removed with LEVY but without deviation cost

If the 2-tier levy is implemented then much like in the bulker section, its effects in the ROI of the OCCS system are going to be more important than the

market of CO2 and the deviation cost.

The installation will make absolute sense especially in the younger vessels as even if the price that the company pays for the CO2 to be removed is 100\$ per ton and the deviation cost burdens the owner, the ROI remains below 10 years in all vessels categories.

If the owner manages to make an agreement to sell the CO2 and comes to an understanding with the shipper for the deviation cost, then the ROI can be as low as 2 years, meaning that it will deliver significant benefits for the owner during the vessel's lifetime.

Both the deviation cost and the CO2 market keep making an impression on the ROI. Especially the CO2 market might make the difference in the decision of the owner when it comes to older vessels as it might reach 10 years.

The deviation cost by itself will make a smaller impression on the ROI but it is something that still needs to be considered as a factor in the final decision.

5.2.3 Conclusions for the tankers section

Like in the bulker section the conclusions for the tanker section can be separated into 2 different categories.

A. Without 2-tier levy the market of the CO2 will play a significant role in the decision of the shipowner about whether it is a sound investment or not to install the OCCS system, since the ROI, if the vessel must pay for the CO2 removal, almost always exceeds 10 years. So, a strong agreement with a suitable buyer must be made before the installation. The deviation cost this time is more important than it was in the bulkers section and its existence will prolong the ROI period substantially, so for the system to be installed an understanding with the shipper will also be necessary.

B. With the 2-tier levy implemented the installation of such a system, especially in vessels under 10 years, will provide significant benefits in the long run as depending on the type of vessel and the market of the CO2 the ROI might be as low as 2 years, which means that the vessel will receive significant benefits from this system. The deviation cost will again play an important role.

6. Conclusion

Taking into consideration the necessity to diminish the CO2 imprint of human activities on this planet, the shipping industry must play its part.

Given the fact that 95% of the existing fleet cannot operate with fuel that will be eco-friendly a solution has to be found for these vessels to decrease their CO2 emissions.

The OCCS system is such a solution that can be installed in almost every existing vessel, but the price of such an installation is not a minor one.

That means that an owner must keep in mind some parameters prior to deciding on such an installation.

If the 2-tier levy is not implemented in MEPC 84 on October 2025, then for this type of system to be installed in a bulker or a tanker, the owner has to first make sure that for the following years he will be able to sell the CO2 captured to a facility and not have to pay for it to be offloaded.

An agreement with the perspective shipper for the deviation cost will play a role in the decision also but not as an important one.

The age of the vessel will always have to be considered.

If the 2-tier levy is implemented, then this system will make sense in all cases.

Again, an agreement to sell the CO2 will help reduce the ROI significantly and an agreement for the deviation cost will further reduce the time needed for the ROI, but in all cases the major contributor to the decision will be the cost of the 2-tier levy if this system is not installed.

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