Emissions From Marine Transportation

A Review on Marine Policy Instruments

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Introduction

Marine transport produces emissions output to the atmosphere, accelerating climate change, but also into the ocean when SOx emissions are blended with waste ballast water, altering the ocean's pH. To shed some light on the status quo of emissions from maritime shipping, this report aims to cover some policy instruments, of various types and different scopes, that it operates under. In addition, our own policy instrument aiming to reduce waste water dumping into the ocean of the Baltic Sea is derived through a simplistic quantification, and designed as a Sulphur Emission Controlled Area (SECA). Moreover, the technical background of the presented policy instruments, their expected outcomes and impacts will be covered and assessed. This is then nuanced by elaborating on how emissions are monitored, as well as how policy instruments are followed-up and adjusted over time. Lastly the report ends with a discussion, in which the different policy instruments are evaluated. Adaptations that may render better results are suggested as well as an elaboration on if and why they're actually realistic in essence.

Economic Policy Instruments

Description of Economic PI's in General

Economic policy instruments are intended to influence the behavior of actors in a desirable way by incentivizing actors to take, or refrain from taking, certain actions. Subsidies are one example often employed to have innovation more rapidly progress towards an expansion phase. As was the case with solar cells which were expensive and of low efficiency early on, but at several critical points saw larger investments from private actors, shortly after subsidization by governments, and now is deemed mature enough to self-sustain due to its higher efficiency and lower cost.[1] Moreover, EPI's closely related to maritime transportation are those of trade restrictions and import/export fees, which may impact domestic production negatively in certain regions, but ensure economic growth and efficiency in a globalized world.[2] As a consequence climate suffers since emissions from the combustion cycle follow from the distribution of goods across seas, which is why taxation on pollutants may help in this regard, as well as bonuses granted to those minimizing their footprints.[3]

Chosen Scope of EPI Investigation - International Maritime Carbon Taxation

A maritime carbon tax is a tax based on the carbon emissions output from the combustion cycle. Such tax covers only CO2 emissions, but could also cover other greenhouse gases, such as methane, by taxation based on its CO2-equivalent global warming potential, where the difference in potency and residence time gives an equivalent measure. Pricing carbon is deemed the most cost efficient way to transition to more climate friendly alternatives and technology.[4] The price of carbon is 1200 SEK or 118 EUR per tonne of fossil carbon dioxide emitted. However, sustainable biofuels, where no net increase in carbon dioxide is seen, are no target to carbon taxation.

For the Swedish level there is a carbon tax, but the maritime sector is exempted[5], and today there is no international maritime carbon tax. In contrast, since 2005, the European Union has had a taxation on GHGs produced by industry under the European Union Emission

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[1] https://www.diva-portal.org/smash/get/diva2:1411106/FULLTEXT01.pdf, The Impact of Subsidies in the Solar Energy Market, A bachelor thesis project conducted by Jesper Larsson and Tobias Ekblom at Uppsala University, 2019.

[2] https://www.fao.org/3/w7541e/w7541e08.htm#6.1.2%20trade%20and%20exchange%20rate%20polices, Guidelines for the integration of sustainable agriculture and rural development into agricultural policies, by J Brian Hardaker under the FAO - Food and Agriculture Organization of the United Nations, Rome 1997.

[3] https://www.weforum.org/agenda/2021/06/addressing-climate-change-through-carbon-taxes/, Addressing climate change through carbon taxes, an article written in the World Economic Forum by Aimée Dushime, 2021.

[4] https://www.government.se/government-policy/swedens-carbon-tax/swedens-carbon-tax/, Sweden's Carbon tax, Government Offices of Sweden, 2022.

[5] https://taxfoundation.org/sweden-carbon-tax-revenue-greenhouse-gas-emissions/#Base "Looking Back on 30 Years of Carbon Taxes in Sweden", Tax Foundation, Samuel Jonsson, Anders Ydstedt and Elke Asen, 2020.

Trading Scheme (EU ETS) which provides a trading system with which actors trade emissions annually within the set cap. While the cap is strained over time, industries transition towards less emitting operations. Due to this system being the most cost effective on the international level, we wanted to investigate why the maritime transport sector does not operate under a similar model.

We found that in mid 2023, a phase II european maritime carbon tax will be employed.[6] Developed under IMO's "ISWG-GHG 12"-project, the protocol provides a limit to how carbon intense ships can be to avoid carbon taxation. In this phase, it does so by providing guidelines on technical and operational solutions to have actors be more energy efficient, hence less carbon intensive, with the goal for year 2030 set to an average reduction of 40 % in carbon intensity, compared to 2008's level. The tax is based on GHG fuel standards, as well as carbon pricing set by market measurement elements (undecided as of right now), if actors were to not comply with the fuel standard and carbon intensity limit. Overall, IMO believe carbon taxation under this taxation method is effective, comes at low cost and is easy to implement across seas.

Ultimately, for the tax to be effective we believe there are some aspects that need consideration. Firstly, there is need for reasonable alternatives (e.g. alternative fuels and emission reduction technology) to be successful, otherwise the tax is limited to fuel standard and energy efficiency compliance, while transitioning to different fuels may largely remove carbon from the emissions palette altogether, thus meeting the intended goal of the carbon tax more effectively (which is why we also studied research and development PI's, more on this later). Secondly, energy efficiency in and of itself should not be an end term goal, since the same amount of distribution of goods in principle can occur, although at a slower pace simply by having more cargo ships sail, thus limiting the potential emissions reduction. Lastly, by consultation with stakeholders there needs to be decisions made towards where the revenue will be spent, one alternative being the continued funding towards the development of emissions reduction technology[7].

Expected Outcomes and Consequences

Overall, we believe carbon emissions will decrease with time, based on the presumed behavioral responses to taxation. Most actors will in short-term be more energy efficient and comply with fuel standards by incorporating technological innovation such as dual fuel injection systems and hybridly run on alternative and fossil fuels. In the long-term, fossil fuel combustion will be limited, and the maritime fleet will mostly run on alternative fuels (mainly produced from biomass or hydrogen gas) incorporating various technological solutions as well.

We also envision that revenue from carbon taxation put towards the development of alternative fuels, may induce a positive feedback loop in the carbon emissions reduction, accelerating the aforementioned development. However, with a different emissions palette from the expanded usage of alternative fuels comes the risk of increased global warming if

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[6] https://www.imo.org/en/MediaCentre/PressBriefings/pages/ISWGHGMay2022.aspx, ISWG-GHG 12: Reducing GHG Emissions from Ships, IMO, 2022.
[7] https://doi.org/10.5089/9781484374559.001 "Carbon Taxation for International Maritime Fuels: Assessing the Options", Ian W.H. Parry, Mr. Dirk Heine, Kelley Kizzier, and Tristan Smith, 2018.

other potent greenhouse gases are produced in the combustion cycle, indicative of the need for broader policy coverage across the global emissions palette. The same reasoning we believe is true for the risk of increased local emissions.

Assessing the PI

In order to establish energy efficiency compliance, IMO stipulates calculations that must be reported by all ships above 400 giga tonnes, which compared to a baseline considerate of various ship types, gives a rating on compliance. These calculations are the attainted Energy Efficiency Existing Ship index (EEXI), and the annual operational Carbon Intensity Indicator (CII). The former one being a measurement on the technical status of the ship needs approval by IMO just once, and the later one defined as GHG emissions output from the amount of cargo transported over distance traveled, is a measurement reported annually.[8] Based on these, ratings are granted, starting 2024. Those rating poorly must provide a plan on how they will improve their rating going forward. This way IMO monitors the PI and based on this data they will review the rating system and provide adjustments going forward, in 2026 at the latest.[9] We believe further adjustments to the carbon taxation policy instrument may likely be taxation based on CO2eq GWP if other greenhouse-gasses were to become largely present in the combustion fumes.

[8] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx, IMO's work to cut GHG emissions from ships, IMO, 2022.
[9] https://www.imo.org/en/MediaCentre/PressBriefings/pages/CII-and-EEXI-entry-into-force.aspx, Rules on ship carbon intensity and rating system enter into force, IMO, 2022.

Legislative Policy Instruments

Description of Legislative PI's in General

Legislation is an authoritarian instrument applied to change decisions and behaviours of actors and accomplish stated standards. LPI's can allow, prohibit or require certain orders that those concerned must pursue. The difference between LPI's and others is that legislative regulations, in contrast, are mandatory.[10]

There are three different groups of relevant acts and regulations, that act under different scopes and extents. Firstly international agreements, often conventions that are binding for states, which are obligated to create national rules accordingly[11]. Secondly, EU law consisting of directives, treaties and regulations, superior to national rules and regulations. EU regulations are directly applicable while directives require implantation in the nation's legal system[12]. And thirdly, the national laws, ordinances and regulations.

Chosen Scope of LPI Investigation - IMO's Annex VI : Fuel Standards, Combustion Concentration Limits and ECAs

With an international carbon taxation PI acting on the EU level, dealing with global emissions which accelerate climate change and affect all of the Earth, we deem PI's dealing with local emissions worthy. Mainly because we believe local emissions will increase as a consequence thereof, affecting the local environment and ecosystems negatively.

We found that IMO in their work to protect the marine environment conducted several PI's (annexes I through VII), some of which aim to reduce emissions from operations and accidental causes. It does so under the International Convention for the Prevention of Pollution from Ships (MARPOL), in which ships are required to follow stated standards for emissions reduction technology and fuel standards, such as limits set on certain fuel concentration contents[13], amongst many other things. The latter one is of most interest to us.

Nitrogen oxides and sulphur oxides (NOx and SOx), as well as various particulate matter (PM), are emissions dealt with in Annex VI - Regulations for the Prevention of Air Pollution from Ships, as the treaty was adopted 1997 and entered into force 2005, during which the limits of fuel sulphur content and NOx concentration present in the combustion fumes respectively were set. Over time the SOx limit became more strict, and from January 2020 the global limit is 0.5 %. In the same treaty, MARPOL designed ECAs aiming to alleviate

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[10] https://www.trafa.se/globalassets/pm/2018/pm-2018_2-abc-om-styrmedel.pdf, "ABC om styrmedel 2018:2), Trafik Analys, Stockholm, s.13.
[11] https://www.trafa.se/globalassets/pm/2018/pm-2018_2-abc-om-styrmedel.pdf, " ABC om styrmedel 2018:2), Trafik Analys, Stockholm s. 13.
[12] https://www.trafa.se/globalassets/pm/2018/pm-2018_2-abc-om-styrmedel.pdf, " ABC om styrmedel 2018:2), Trafik Analys, Stockholm s. 14.
[13] https://www.imo.org/en/about/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx, International Convention for the Prevention of Pollution from Ships (MARPOL), IMO, 2022.

regions of particular concern from heavy continued type-specific pollution[14]. Since January 2015 several regions, such as the Baltic sea, are deemed to be SECA's, where the limit of sulphur emission concentration is set to 0.1 %. There are also NECAs, where the allowed NOx combustion limit varies from 2.0 to 17 [g/kWh] depending on the type of ship engines (They are divided into tiers (I through III) depending on their year of production).[15]

Expected Outcomes and Consequences

IMO deems that as NOx has been regulated its emission concentration has decreased, but has consequently given rise to increased particulate matter and sulphur emissions. The former one is mostly due to combustion technicality, while the latter one is due to ship actors employing open loop scrubbers (to be NOx compliant), where the emission fumes are scrubbed and blended with waste ballast water, which is then dumped into the ocean, altering its pH. This is the main reason for the global sulphur limit and SECAs being applied. IMO deems that the global sulphur limit sparked a smooth transition from HFO to Very Low Sulphur Fuel Oil (VLSFO) since refineries were able to provide the latter to a large majority, giving rise to a 70 % reduction of sulphur emissions.[16]

Assessing the PI

The implementation of ECAs and the global sulphur limit has been one way IMO in real time assessed the status quo and adapted the PI which thereafter rendered better results. Moving forward, we believe further adjustments to Annex VI may likely be several new ECAs using more stringent methods to control the emissions, such as the HFO ban in the arctic region[17]. Moreover, in the light of assumed advancement in emissions reduction technology and engine efficiency, we also believe a Tier IV list may likely be due, where more stringent values of allowed NOx emissions are presented.

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[14] https://www.imo.org/en/ourwork/environment/pages/air-pollution.aspx, Prevention of Air Pollution from Ships, IMO, 2022.

[15] https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx, Nitrogen Oxides (NOx) – Regulation 13, IMO, 2022.

[16] https://www.imo.org/en/MediaCentre/PressBriefings/pages/02-IMO-2020.aspx, IMO2020 fuel oil sulphur limit - cleaner air, healthier planet, IMO, 2021.

[17] https://www.reuters.com/business/energy/un-adopts-ban-heavy-fuel-oil-use-by-ships-arctic-2021-06-17/, UN adopts ban on heavy fuel oil use by ships in Arctic, Reuters, 2021.

Research and Development Policy Instruments

Description of R&D PI's in General

R&D PI's are due to the maritime market needing new fuel types as well as advancement in emissions reduction technology and energy efficiency. R&D PI's often rely on EPI's and LPI's for its progression, because they're best prolonged when provided funding, often by governments and relevant organizations through loans or grants, but also when adjacent actors are engaged in the solutions being developed. Governments often spark this interest by tax deduction and bonuses granted, which ultimately lowers the threshold for the R&D seeing investments. Requirements that vessels must be equipped with certain types of technology is one practical example of an LPI encouraging R&D. It can also be conducted effectively by having competence be matched through collaboration, one example being academia and industry using their joint knowledge to come up with innovative solutions.

Within the R&D domain there are also policies at different levels which look into a broad set of solutions. Profound is that the EU funds innovation, via their innovation fund and Horizon Europe, for highly innovative technologies, by providing support to both big flagship and small-scale projects with a focus on low-carbon technologies. On the Swedish level there is a large contribution to research and development from the government, ruling that more than 3% of GDP must go to R&D with green technology being one of the focus areas. The funding for R&D goes through the agency VINNOVA[18], where one is able to find ongoing as well as finished projects.

Chosen Scope of R&D Investigation - EU Funding Towards Methanol Fuel Compatibility : The Case of the Retrofitted Stena Germanica

Having looked into E- and L-PI's, we think R&D PIs are necessary to enable more stringent measures and policy within the former two. For example, we believe improved efficiency within already known (or the emergence of new) technical solutions and the emergence (or development of already present) alternative fuels will make the EU carbon taxation more just. In essence, when there are reasonable alternatives to orient towards, it is more fair to increase the tax in a nudging manner. The same reasoning we believe is true in an LPI aspect.

Now, since we give credence to the carbon taxation being the most effective when revenue from the tax is put towards funding R&D of alternative fuels we decided to look into one such PI, instead of R&D PI's oriented towards improving energy efficiency, the other presupposed need when implementing carbon taxation. Moreover, it is crucial that the maritime sector has compatible alternatives to fossil fuels since the maritime fleet is difficult to electrify, unlike the road transport sector. One such fuel is methanol, which can either be synthetically produced by hydrogen gas from electrolysis and carbon dioxide or from biomass.[19]

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[18] https://sweden.se/work-business/business-in-sweden/a-country-of-innovation, "Sweden has long fostered innovation and entrepreneurship. Here's how.", Sweden.se, 2022.
[19] https://f3centre.se/sv/faktablad/elektrobranslen/, Elektrobränslen, f3 centre - Svenskt Kunskapscentrum för Förnyelsebara Drivmedel, 2021.

When investigating R&D PI's we found that Stena Line in collaboration with Chalmers University of Technology conducted a research project funded by the EU Innovation Fund[20]. The project is called "*Methanol: the marine fuel of the future*"[21], and aimed to develop methanol fuel as an alternative fuel for the Stena Germanica ferry going between Gothenburg and Kiel to meet the SECA sulphur limit. The project finished in 2015, and was deemed successful.

Expected Outcomes and Consequences

The cost of transitioning to methanol was expected to be relatively low due to the possibility of retrofitting the engines in the vessel as well as there only needing to be minor changes conducted to the bunker infrastructure, both due to methanol being a liquid, just like HFO, compared to the alternatives, such as LNG (being gaseous). The outcome of the project was a change towards methanol fuel being used in the Germanica continuing on, which was deemed a successful result since Stena were able to comply with the sulphur limit in time with the BSR being of SECA status. Methanol, being sulphur free, has no sulphur emissions and also complies with the Tier III NOx limit, which is good, even though the BSR is not of NECA status, Stena Germanica lowered its NOx emissions by running on methanol instead of marine diesel.

So while the Stena Germanica project was successful, lifting the perspective, the major downside of methanol is that methanol produces methane emissions in its combustion cycle, a 20-30 times more potent greenhouse gas than carbon dioxide[22]. Biomethanol may also be associated with indirect emissions, if produced by crops grown on fields that saw land use change and conversion, such as deforestation.

Assessing the PI

We believe that a demand of methanol globally gives an opportunity for refineries finding a new market when road transport will be largely electric, (more on this in the Discussion). In essence, methanol fuel is SECA- (and potentially NECA-) compliant, as was the case with the Stena Germanica retrofitted for methanol fuel operation, while giving rise to little or no net GHGs emissions if it is synthetically produced utilizing carbon dioxide output from parallel processes. As is the case of the Stena Germanica which since 2021 utilizes methanol from residual steel gases[23], or biosynthetically if utilizing waste biomass from various industries.

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[20] 2012-EU-21017-S | Innovation and Networks Executive Agency (europa.eu), "2012-EU-21017-S", INNOVATION AND NETWORKS EXECUTIVE AGENCY, 2012.

[21] FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf, "Methanol as a marine fuel report", Karin Andersson CTH, and Carlos Márquez Salazar, Methanol institute, 2015.

[22] https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf, "Global Warming Potential Values", Greenhouse Gas Protocol, 2016.

[23] https://www.stenaline.com/media/stories/stena-germanica-refuels-with-recycled-methanol-from-residual-steel-gases/, "Stena Germanica refuels with recycled methanol from residual steel gases", Stena Line, 2021.

Our Own PI Fabrication

Implementing a SECA Based on a Chemistry Calculation

Based on the chemistry calculation conducted in the Appendix we decided to fabricate our own PI. The sulphur trioxide concentration, [SO_3], allowed to at most be 1.5 % in any fuel may likely ensure that oceans that are above a pH value of 7, will remain above 7. The global sulphur limit of 0.5 %, stipulated by IMO, already acts in this manner. Therefore, a more stringent value can be used in critical regions, such as the BSR. We believe that if the BSR (already deemed a SECA) adopted the more strict value of 0.05 % rather than IMO's SECA sulphur limit of 0.1%, it would be more fit for decelerating its pH alteration and eutrophication of coastal waters. This is important since the Baltic sea region sees little mixing with the adjacent Atlantic Sea due to the narrow entrance, and in certain areas has a pH of 6.5[24]. Therefore, our own fabricated PI has the following practical implications. Boats entering the Baltic Sea Region must have a fuel sulphur content less than 0.05 % or else face taxation. The taxation will be based on the amount of time surpassed since the employment of this PI, entering into full force after three years of its adoption, as well as the exceedance of the allowed limit according to an exponential curve since pH is sensitive in the inverse manner. The revenue of the taxation will be put towards the restoration of ecosystems in the BSR and the continued research and development of alternative fuels with little or no sulphur content.

Expected Outcomes and Consequences

We believe our own developed PI will be in line with the results acquired from IMO's global sulphur limit and SECA status, but be of larger magnitude due to the more stringent value. Ultimately, the BSR pH may recover, although at a very slow pace since oceanic processes such as pH restorations act under long time constants (centuries). The same, we believe, is true for the coastal areas suffering due to the acidity and eutrophication.

Furthermore, scrubbers technology has not been accounted for in our calculation. An adaptation that will render a more fair result is therefore that actors with scrubbers reduction technology employed will still face taxation under the exponential curve but times a constant $k = (1-c)$, where $0 < c < 1$ is another constant being the effectiveness of their scrubber.

Assessing the PI

The derived function works well in close proximity to pH = 7, but has little ground at extreme points. The assumption that an oceanic dynamic system in a purely mathematical manner can be solved under a linear system of equations relinquishes the fact that all equilibrium constants are unable to be true simultaneously. Moreover, they are coupled with depth, which supports the usage of a linear system, but the equilibrium constants are known to occur at different depths, which thus makes the mathematical model somewhat imperfect yet

24 https://www.lansstyrelsen.se/download/18.3da1c377162bd90d9eef023/1526068899897/Ostersjon_Ask_Laxa.pdf, "Faktablad om östersjön", Länsstyrelsen i Örebro Län, 2017.

again. In addition, the alkalinity of the ocean, a measurement of its ability to resist pH from changing, has not been accounted for in our calculation, to simplify the chemistry. Nevertheless, its incorporation would yield less strict values for the allowed sulphur trioxide concentration, based on the “strength” of resistance associated with oceanic alkalinity. In the case of the BSR, its buffer capacity is deemed as weak[25]. In addition, the equilibrium constants themselves are functions of temperature, alkalinity and pressure as mentioned in the appendix, (and can be researched more on by recursing in to the cited studies). All together, this results in a margin of error to our result. Despite this, we believe our calculation is impactful, and in extension, quantifying the upper and lower bounds for emission limits in ECAs.

25 https://www.lansstyrelsen.se/download/18.3da1c377162bd90d9eef023/1526068899897/Ostersjon_Ask_Laxa.pdf, “Faktablad om östersjön”, Länsstyrelsen i Örebro län, 2017.

Discussion

This text was initiated with the potential that the EPI of international maritime carbon taxation may have in reducing global emissions, but also the assumed increase of local emissions, as a consequence thereof. This was assumed to be “dealt with" by elaborating on the effect NECAs historically has had and its continued important role today, being that they’ve helped reduce NOx emissions and thus improved the conditions of the local environment. Unfortunately, NECA’s induced emission reduction of the exhaust fumes gave rise to waste water ballast dumping into the ocean instead, altering the oceans pH due to the large sulphur content in the HFO’s. The global sulphur limit and various regions granted the SECA status dealt with this issue. In addition, the policy instrument of R&D aiming to spark the innovation of methane fuel production fit for maritime vessels showed its potential in complying with the SECA, but also the NECA regulations. Moreover, R&D also has the potential to loop back to the PI of carbon taxation, if the revenue from the tax goes towards innovation of more suitable alternatives, such as methanol. While the alternative fuels develop towards large scale, our own fabricated PI may be very effective, if employed, in dealing with the BSR’s fundamental problem of perpetual acidification due to acidic ballast waste water dumping and it seeing little mixing with the Atlantic Sea.

In our opinion, we believe the R&D PI showing the potential of methanol fuel being well fit for marine vessels is the best PI amongst the ones elaborated on here. Mainly, because it shows an alternative to emissions reduction technology in being compliant to regulations, but also because it proved to show compliance to the LPI of ECAs and has the potential to be in compliance with the EPI of carbon taxation if methanol fuel production is conducted in such a way that the process is of net zero GHG equivalent emissions. And lastly, because the R&D of alternative fuels is necessary for more stringent regulations in the EPIs and LPIs respectively. Conversely, if the methanol fuel production has large upstream GHG emissions, the R&D PI and EPI largely counteract one another, possibly making global warming worse.

Nevertheless, under the dependencies of methanol fuel production enabling more stringent carbon taxation and ECA compliance, we believe the marine sector is fully operable under these regulatory conditions, given that tomorrow’s refineries were to provide bio and electrofuels in a net zero GHG emissions manner. They can do so by having solar cells or wind turbines produce renewable energy locally, since this could be used to produce hydrogen gas, via electrolysis. Then, pipelining carbon dioxide output from the emissions of a parallel biofuel production process, the carbon dioxide can in an electrolytic process be utilized to produce electrofuels, such as methanol. Ultimately, the parallel production of, on one hand sustainable biofuels, enclosing the carbon cycle, acts as a sink and the carbon utilization in the electrofuels, emulating a sink since it has found a domain of utilization and therefore is not a target of Carbon Capture and Storage (CCS), has more than double the benefit than these two processes have decoupled. Hopefully this enables a (close to) net zero GHG emissions process. All together, refineries can produce bio and electrofuels to the maritime transportation sector which is difficult to electrify, in contrast to the road car transportation sector, where their segment is decreasing as more and more electric vehicles are produced, and old cars are phased out.

Appendix

The development of sulphur dioxide residing in the ocean follows

$$SO_2 + H_2O <=> H_2SO_3 <=> H^+ + HSO_3^- <=> 2H^+ + SO_3^{2-}.$$

Now, depending on oceanic water properties, mainly those of salinity, temperature and alkalinity the following thermodynamic oceanic properties hold.

$$(0.032 \pm 0.01\,[mol/kg] =)\ K_{PS} = \frac{[SO_2(aq)] + [H_2SO_3]}{P_{SO_2}} = \frac{A+B}{C}, \qquad [26](1)[27]$$

$$(0.0139 \pm 0.004\,[mol/kg] =)\ K_{1SO_3} = \frac{[H^+]\,[HSO_3^-]}{[SO_2(aq)] + [H_2SO_3]} = \frac{D*E}{A+B}, \qquad (2)[28]$$

$$((6.5 \pm 0.5) * 10^{-8}\,[mol/kg] =)\ K_{2SO_3} = \frac{[H^+][SO_3^{2-}]}{[HSO_3^-]} = \frac{D*F}{E} \qquad (3)[29]$$

Incorporating symbols for these equations, and solving for the ionic hydrogen concentration the oceanic pH can be obtained via, $pH = -\log_{10}([H^+])$.

$$K_{PS} = \frac{[SO_2(aq)] + [H_2SO_3]}{P_{SO_2}} = \frac{A+B}{C},\ where\ A = [SO_2(aq)],\ B = [H_2SO_3],\ C = P_{SO_2} \qquad (1)$$

$$K_{1SO_3} = \frac{[H^+]\,[HSO_3^-]}{[SO_2(aq)] + [H_2SO_3]} = \frac{D*E}{A+B},\ where\ D = [H^+],\ E = [HSO_3^-], \qquad (2)$$

$$K_{2SO_3} = \frac{[H^+][SO_3^{2-}]}{[HSO_3^-]} = \frac{D*F}{E},\ where\ F = [SO_3^{2-}] \qquad (3)$$

Using the following simplifications,

$$K_{PS} = \frac{A+B}{C} <=> B = K_{PS} * C - A \qquad (\text{ rearranged (1) }) \Leftrightarrow (1^*)$$

$$K_{2SO_3} = \frac{D*F}{E} <=> E = \frac{D*F}{K_{2SO_3}} \qquad (\text{ rearranged (3) }) \Leftrightarrow (3^*)$$

$$K_{1SO_3} = \frac{D*E}{A+B} <=> D = \frac{K_{1SO_3} * (A+B)}{E} = [H^+] \qquad (\text{ rearranged (2) }) \Leftrightarrow (2^*)$$

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[26] https://research.chalmers.se/publication/106400/file/106400_Fulltext.pdf Seawater Scrubbing - reduction of SOx emissions from ship exhausts, by Dr Ida-Maja Karle and Prof David Turner, Dept of Chemistry of GOT University under the The Alliance for Global Sustainability, Göteborg 2007.
[27] https://nvlpubs.nist.gov/nistpubs/jres/090/jresv90n5p341_a1b.pdf, Thermodynamics of Solution of SO2(g) in Water and of Aqueous Sulfur Dioxide Solutions, by R.N. Goldberg and V.B. Parker under the National Bureau of Standards, Gaithersburg, MD 20899, 1985.
[28] same pdf as referral 27.
[29] same pdf as referral 27.

substitution of (1*) and (3*) into (2*) gives,

$$D = \frac{K_{1SO_3} * (A + B)}{E} <=> D^2 = \frac{K_{1SO_3} * (A + (K_{PS} * C - A) * K_{2SO_3})}{F} => D = \pm\sqrt{\frac{K_{1SO_3} * (A + (K_{PS} * C - A) * K_{2SO_3})}{F}} =$$

$$\pm\sqrt{\frac{K_{1SO_3} * ([SO_2(aq)] + (K_{PS} * P_{SO_2} - [SO_2(aq)]) * K_{2SO_3})}{[SO_3^{\ 2-}]}} = [H^+]$$

from which the oceanic pH comes out to be

$$- log_{10}(+\sqrt{\frac{K_{1SO_3} * ([SO_2(aq)] + (K_{PS} * P_{SO_2} - [SO_2(aq)]) * K_{2SO_3})}{[SO_3^{\ 2-}]}}) = pH$$

In this context the above derivation makes pH a function of sulphuric trioxide concentration (a precursor to sulphur dioxide) since the solubility of sulphur dioxide, the equilibrium constants and the partial pressure of SO2 vary somewhat depending on environmental conditions, but are assumed to be constant. In contrast, the sulphur trioxide concentration is the only variable susceptible to change via regulation by a policy instrument.

So, inversely, solving for $[SO_3^{\ 2-}]$ gives the sulphur trioxide concentration as a function of pH

$$[S0_3^{\ -2}] = K_{1SO_3} * (- e^{pH}) * (([SO_2(aq)] * (K_{2SO_3} - 1)) - (P_{SO_2} K_{PS} * K_{2SO_3}))$$

Using the fact that K2SO3 is very small, the expression simplifies to,

$$[S0_3^{\ -2}] = K_{1SO_3} * (- e^{pH}) * (- [SO_2(aq)]))$$

and is no longer a function of the partial pressure. Moreover, it is now only a function of just one equilibrium constant (and not three), the “desired” pH and the solubility of sulphur in water.

Using the best known value for the equilibrium constant, and the solubility of SO2 in water, makes the sulphur trioxide concentration at most be **1.5 %** to assure an arbitrary ocean stays just above **pH = 7**.

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