MTM Compliance Cost Calculator: concepts, fuel costs, and compliance strategies

1 Introduction

This document develops the internal logic for the MTM Compliance Cost Calculator (MCCC), connecting fuel cost calculations to their economic rationale. It explains the underlying optimization problem and shows that the modeled strategies are subsets of this problem.

1.1 Set-up

Ships (vessels) choose a quantity of fuel q, measured in energy units, such as MJ or GJ, generating emissions, e, measured in the mass of greenhouse gases emitted per unit energy, for example $\text{gCO}_2\text{eq/MJ}$.

The ship chooses its fuel mix given regulations, including a so-called "technical element" and an "economic element". The technical element or "goal-based fuel standard" (GFS) is a rate-based limit on the average emissions intensity over time, $\bar{e}$, which decreases over time and is similarly measured in $\text{gCO}_2\text{eq/MJ}$. (Here and throughout, all quantities and variables are indexed by t, which we omit for neatness.)

The mass of emissions above the rate-based limit may be subject to a penalty, the "remedial unit" (RU), denominated in a price per tonne of CO_2eq. If a so-called flexible compliance mechanism is included, emissions that are below the rate-based limit ($e < \bar{e}$) are "surplus units" (SU), and can be used by other vessels to offset their liability of excess emissions ($e > \bar{e}$) that would otherwise require the purchase of RUs. The economic element, in turn, is a flat tax payable for all emissions e.

Finally, the regulations may include incentives for specific fuels, the so-called "zero or near-zero fuels" (ZNZs). This is a financial payment for all emissions abatement achieved by using ZNZs. These fuels could be defined based on a positive list approach or based on their characteristics. Here, we define them based on whether they achieve emission reductions relative to the baseline emissions of fossil fuels. (For example, a 90% reduction relative to the baseline emissions of LSFO would select on fuels with emissions intensities of $.9 \times 94.3$ $\text{gCO}_2\text{eq/MJ}$, or 9.4 $\text{gCO}_2\text{eq/MJ}$ or below).

1.2 Costs are a function of fuel costs and regulatory drivers

The total cost of fuel is the sum of underlying fuel cost(s), c, measured in cost per unit energy, and the additional cost drivers introduced through regulations. Indexing types of fuel (for example, fossil fuels and low-emission ZNZs) with i

$$\underbrace{TC(\cdot)}_{\text{Cost function}} = \underbrace{\sum c_i \cdot q_i}_{\text{Fuel cost}} + \underbrace{L(\cdot)}_{\text{Levy}} - \underbrace{Z(\cdot)}_{\text{ZNZ Reward}} + \underbrace{R(\cdot)}_{\text{Remedial Unit}} + \underbrace{S(\cdot)}_{\text{Surplus Unit}}$$

The regulatory cost or incentive drivers are functions of fuel specific intensities, e_i and the amount of fuel used (in energy units), q_i, or the *average* intensity of the vessel's fuel mix, $e = (\Sigma_i e_i q_i)/(\Sigma_i q_i)$:

- Levy:
$$L(e_i, q_i, \ell) = \ell \cdot (\Sigma_i e_i q_i).$$
- ZNZ reward
$$Z(\bar{e}, e_i, q_i, z) = z \cdot \Sigma_i(\,\bar{e} - e_i\,)q_i \quad \forall\, i \in \{\text{ZNZ}\}.$$
- Remedial Units
$$R(e, \bar{e}, r) = \max\{(\,e - \bar{e}\,) \cdot r,\ 0\}$$
- Surplus Units
$$S(e, \bar{e}, s) = \max\{\,(\bar{e} - e) \cdot s,\ 0\},$$

The values ℓ, r, s, z are penalty or reward rates defined in terms of cost per mass of emissions, for example USD/tCO_2eq.

Specifically, ℓ sets the rate of the levy on all emissions. If rewards for ZNZs are included for specific fuels ($i \in \{\text{ZNZ}\}$), the quantity of the reward generated is determined in terms of tCO_2eq avoided compared to the intensity limit, $\bar{e}$. Finally, r sets the rate of the Remedial Unit cost on emissions above the threshold mandated by the GFS, and in flexible compliance framework, emissions below the GFS limit can be sold to non-compliant ships at a value per mass of emissions set by the rate s.

We explain how s is determined below.

1.3 "Two-tiered" GFS

Recent discussions have introduced the concept of a two-tiered GFS. In a single-tiered GFS, there is a single intensity limit, $\bar{e}$, in each period. As set out above, this is used to determine the quantity of SU or RU.

A two-tiered GFS imposes an upper and lower limit, which we denote $\bar{e}_H > \bar{e}_L$. In the configuration currently under discussion, intensities in the band between these limits would be liable for a lower tier of RU, $r_L < r$, and would not generate any Surplus Units. Intensities above the upper limit would be subject to the "full" cost of r.

The regulatory cost drivers under a two-tiered GFS would therefore be modified:

$$R(\cdot) = \begin{cases} (e - \bar{e}_L)r_L, & \text{if } \bar{e}_L < e \leq \bar{e}_H \\ (e - \bar{e}_H)r + (\bar{e}_H - \bar{e}_L)r_L, & \text{if } e > \bar{e}_H \\ 0, & \text{if } e \leq \bar{e}_L. \end{cases}$$

2 Optimization problem

We study a sufficiently general problem of a vessel choosing a cost-minimizing combination of a conventional fossil fuel F and a low-emission alternative fuel, denoted A. Without loss of generality, we can normalize energy consumption: $\sum q_i = 1$ and $i \in \{F, A\}$. Then the ship's problem is to choose shares q_i to minimize costs subject to an intensity-based constraint (the GFS):

$$\min\ TC = \sum u_i q_i + R(\cdot) + S(\cdot)$$

where $u_i = c_i + \ell \cdot e_i + z \cdot (\bar{e} - e_{ZNZ})$.

s.t.

$$e = \sum e_i q_i \,/\, \sum q_i \ \leq \ \bar{e}.$$

Again, c_i are fuel-specific costs per unit energy with costs c_F for a higher-emission fossil fuel and c_A for a lower-emission alternative fuel. Generally, $c_F < c_A$ and $e_F > e_A$. (Fossil fuels are cheaper and more polluting).

If $e_F \leq \bar{e}$, then the constraint does not bind, and the cost-minimizing choice is $q_F^* = 1$. Similarly, if the cost of the levy ℓ is sufficiently high, then $c_A + \ell \cdot e_A < c_F + \ell \cdot e_F$. In these cases, the cost-minimizing choice is $q_A^* = 1$ and, again, the constraint does not bind. (This is also true if A is a ZNZ, the reward rate z is high enough and $\bar{e} - e_A$ is large enough: $c_A - Z(\cdot) < c_F$.)

If the constraint binds, using the normalization $q_A + q_F = 1$, gives the familiar optimization problem:

$$\mathcal{L}:\ u_F\, q_F + u_A\,(1 - q_F)\ -\ \lambda\Big[\bar{e} - e_F\, q_F - e_A\,(1 - q_F)\Big].$$

Rearranging the first-order condition gives

$$\lambda\ =\ \frac{u_A - u_F}{e_F - e_A}\ =\ \frac{(c_A + \ell e_A + z(\bar{e} - e_{ZNZ})) - (c_F + \ell e_F)}{e_F - e_A},$$

Here, λ is the shadow price of marginally relaxing the constraint (the Goal-based Fuel Standard) by reducing the share of fossil fuel consumption, q_F, and increasing the share of lower-emission alternative fuel consumption, q_A. It is the marginal cost of abatement using fuel A.

2.1 Comparison with Remedial Units

If the constraint binds, the vessel can choose to reduce emissions by combining fuels / "blending", or choosing only to use fossil fuel ($q_F = 1$) and paying for the resulting excess emissions ($e_F - \bar{e}$) using Remedial Units (RUs). The ship therefore evaluates $\lambda \gtreqless R(e_F, \bar{e}, r)$. If $\lambda < R(\cdot)$, then the ship chooses q_F^*, q_A^* such that $q_F^* < 1$, $q_A^* > 0$.

Substituting the constraint into the objective function and using the normalization $q_F + q_A = 1$ gives

$$q_F^* = \frac{\bar{e} - e_A}{e_F - e_A}, \quad q_A^* = \frac{e_F - \bar{e}}{e_F - e_A}.$$

The total cost is then

$$TC = c_F\, q_F^* + c_A\, q_A^* + L(\bar{e}, \ell) - Z(\cdot).$$

The vessel can generate revenue $Z(\cdot)$ if it chooses to combine the fossil fuel with a ZNZ fuel.

If the constraint binds and $\lambda > R(\cdot)$, the ship chooses to pay Remedial Units:

$$TC = c_F + L(e_F, \ell) + R(e_F, \bar{e}, r).$$

2.2 Surplus units

Under a flexible compliance mechanism, ships that achieve emissions below the GFS-mandated maximum ($e < \bar{e}$) can monetize the value of this "surplus" by selling these unused emissions to non-compliant vessels (those with $e > \bar{e}$). The value of these surplus units may be regulated or determined in a market. To proxy for their value, we set the same as a market clearing condition that the maximum willingness to pay for SUs is determined by the marginal cost of compliance in the market.

Recalling that we define λ_i as the cost of abatement using fuel i relative to a baseline fossil fuel F,

$$\lambda_i = \frac{u_i - u_F}{e_F - e_i},$$

there may be a range of abatement fuels available, determined by the membership of i. Maximally, $i \in \{\text{Biodiesel}, \text{Biomethane}, \text{ZNZ}\}$. If some abatement options are not available, these are excluded from the membership of i.

Then s, the price of surplus units, is set by the intersection of demand for abatement and the supply of abatement generated by overcompliant fuels (those with $e < \bar{e}$, up to the maximum of the price of the Remedial Unit, r).

If, by assumption, the market has absorbed relatively less expensive abatement options, these can be excluded from i. This raises the cost of surplus units and, equivalently, the value of generating this abatement using fuels below the GFS limit.

2.3 Determining the value of Surplus Units

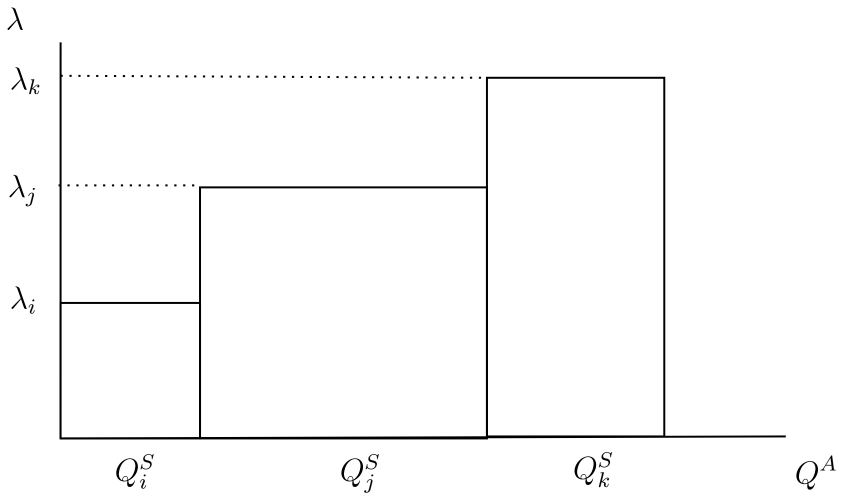
We put structure on the market for abatement to determine s, the market clearing price of the SU. A vessel using fuel i with intensity below the GFS limit generates a mass of surplus emissions relative to the GHG limit ("abatement"):

$$Q_i^S = (\bar{e} - e_i) \cdot q_i \quad | \quad e_i < \bar{e}$$

where, as above, e is in mass CO2eq per unit energy (for example, gCO2eq/MJ), q_i is in amount of energy used, and so Q_i^S, is the mass of abatement or surplus generated, in mass. Then the fleet-wide abatement available from fuel i is total abatement across all ships, V:

$$\sum_{v=1}^{V} Q_{iv}^S = Q_i^A \quad | \quad e_i < \bar{e}$$

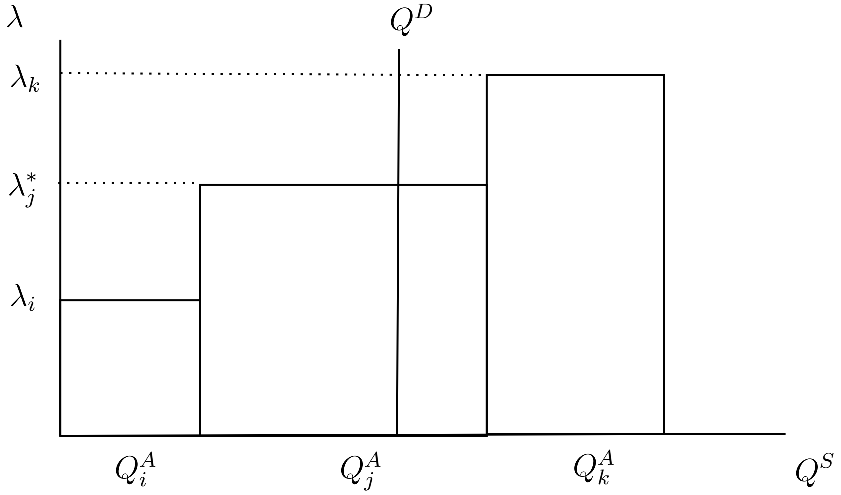
Ordering fuels by the abatement costs λ_i and abatement quantities Q_i^S in (λ, Q^S) space creates the marginal abatement cost curve in some given time t:



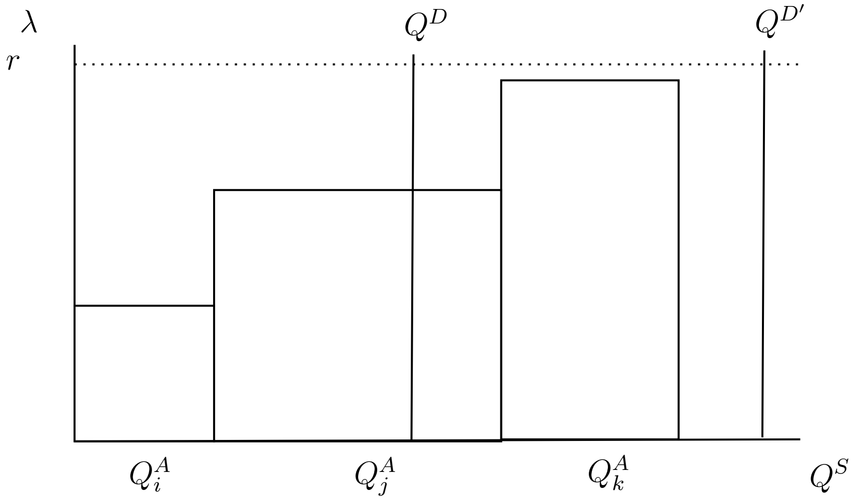
Similarly, let Q^D be the aggregate demand for abatement, which is the sum of the mass of emissions from fuels whose intensities exceed the GFS limit, summed across all vessels, indexed by v:

$$Q^D = \sum_{v=1}^{V} (e_v - \bar{e}) \quad | \quad e_v > \bar{e}$$

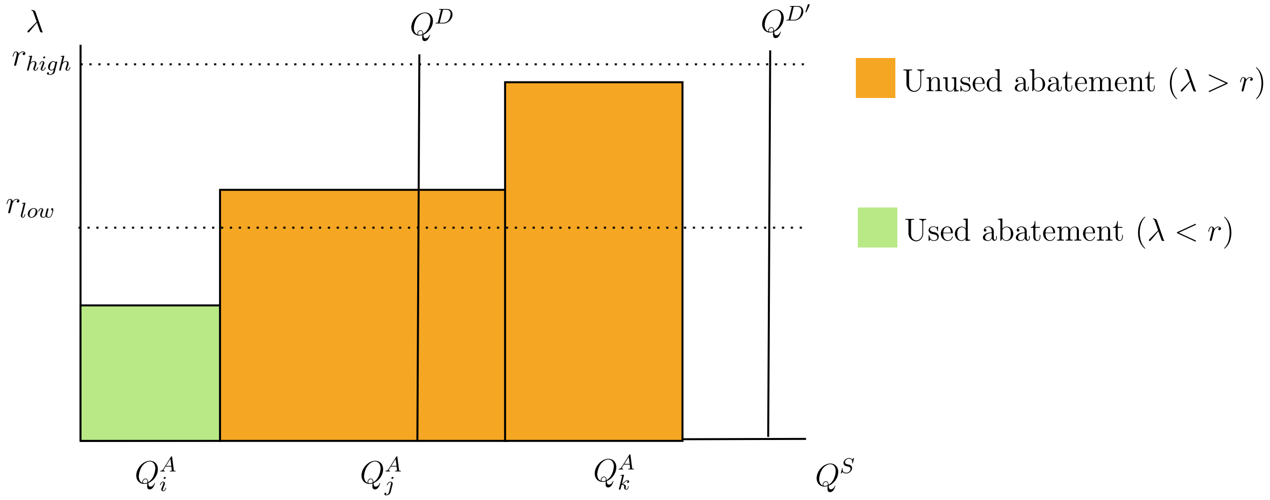
The market clearing price of the SU is defined as the cost λ^* associated with the marginal unit of abatement required, given the level of demand Q^D:



If Q^D exceeds available abatement ($Q^D > \sum Q_i^A$), then it is equivalent to the demand for abatement exceeding supply in the market. This means Q^D can only be satisfied using a non-abatement cost, which is the remedial unit (RU) at cost r. Using $Q^{D\prime}$ for this level of demand (which exceeds available supply of abatement, or Surplus Units):



This market structure is such that the cost of the SU is set by the most expensive unit of abatement required, up to the cost of the RU. This underlines the criticality of the cost of the RU. If the RU price is lower than some abatement cost λ_i, then this fuel i cannot monetize its emission reductions (because it is cheaper to pay the penalty):



3 Calculations

The MCCC applies this logic to determine the best abatement strategy in four potential scenarios:

- $S1$: Using LSFO and the lowest cost between blending biodiesel or paying the RU. The total cost of this strategy includes the price of the fossil fuel, the cost of the levy and the price of least-costly option for compliance (price of biofuel or RU).
- $S2$: Using LNG and the lowest cost between blending biomethane or paying the RU. The second strategy presents the same cost structure as strategy 1 but for a vessel capable of operating on LNG and liquefied biomethane.

- $S3$: Using LSFO and the lowest cost between ZNZ and paying the RU.

- $S4$: Using 100% ZNZ-fuels and then trading the surplus compliance.

S1: Abatement by blending biodiesel

The calculation of strategy 1 is a direct application of the optimizing framework above, with $i \in \{\text{LFSO}, \text{Biodiesel}\}$.

S2: Including Surplus Units

The calculation of strategy 2 has $i \in \{\text{LNG}, \text{Biomethane}\}$ and introduces the value of surplus units. As set out above, the value of surplus units is assumed here to reflect the market-clearing price for compliance.

As before, if the constraint does not bind, $q_F^* = q_{\text{LNG}}^* = 1$. Now, however, the ship may be able to monetize compliance:

$$TC = c_{\text{LNG}} + L(e_{\text{LNG}}, \ell) + S(e_{\text{LNG}}, \bar{e}, s)$$

where $S(i) = (\bar{e} - e_{\text{LNG}})\, s$, with s derived by the assumption or the market clearing price for surplus. If the policy binds, then $e_{\text{LNG}} \geq \bar{e}$ and the vessel evaluates $\lambda_A = \lambda_{\text{biomethane}} \lesseqgtr R(e_{\text{LNG}}, \bar{e}, r)$.

S3: Including ZNZs

Strategy 3 has $i \in \{LSFO, ZNZ\}$, so the ship can combine a fossil fuel, LSFO, with a ZNZ and earn a ZNZ reward factor if regulatory incentives include this incentive. The solution if the constraint does not bind is as above, $q_F = q_{LSFO} = 1$ or $q_A = q_{ZNZ} = 1$. The ship evaluates $\lambda_{\text{ZNZ}} \lesseqgtr R(e_{\text{LFSO}}, \bar{e}, r)$. If it is cost-minimizing to abate using ZNZ, then the emission intensity reduction is attributed to ZNZ and secures a reward. The cost is then

$$TC = c_{\text{LFSO}}\, q_{\text{LFSO}}^* \;+\; c_{\text{ZNZ}}\, q_{\text{ZNZ}}^* \;+\; L(\bar{e}, \ell) \;-\; Z\big(\bar{e}, e_{ZNZ}, q_{ZNZ}^*, z\big),$$

where the last term is the reward function for ZNZ-driven abatement to meet the GFS limit $\bar{e}$ relative to the benchmark of the fossil fuel at reward rate z: $(\bar{e} - e_{ZNZ})z$.

S4: Combining Surplus Units and ZNZ Rewards

Strategy 4 has $i \in \{ZNZ\}$ so enables the case of using only the ZNZ, or $q_A^* = q_{\text{ZNZ}}^* = 1$, combining the surplus and reward. Since $e_{\text{ZNZ}} < \bar{e}$ in most periods/years, this strategy can generate incentives:

$$TC = c_{\text{ZNZ}} + L(e_{\text{ZNZ}}, \ell) \;-\; S\big(e_{\text{ZNZ}}, \bar{e}, s\big) \;-\; Z\big(\bar{e}, e_{ZNZ}, q_{ZNZ}^*, z\big).$$

4 Version control

Subject to continuous edits and improvements; please use the most recent vintage. This version: `v1`.

5 Authors: `v1`

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