NZF Calculator: Concepts

Contents

1 Introduction

This note summarises economic concepts underlying optimizing energy (fuel) decisions by agents (vessels) subject to the IMO's Net-zero Framework (NZF). We focus on the decision making of a marginal (price taking) "regulated entity" (RE).

1.1 Regulation

The RE chooses a quantity of fuel q, measured in energy units, such as MJ or GJ, generating emissions of intensity e, measured in the mass of greenhouse gases emitted per unit energy, for example gCO_2eq/MJ. Multiplying e by energy used, E, converts intensities to mass.

The RE chooses its fuel mix given costs and benefits that are partially determined by the NZF, including a "Global Fuel Standard" (GFS). The GFS is a rate-based GHG fuel intensity (GFI) limit on average Well-to-Wake (WtW) emissions intensity over a given period (likely a year).

As shown in Figure 1, this limit decreases over time and is measured in gCO_2eq/MJ. Reduction rates are "two-tiered", including a *base compliance* target (tier 2), e_B, and a *direct* *compliance* target (tier 1), e_D. These limits are non-binding ("soft"), because the RE can pay for the mass of pollution generated above this limit instead of incurring the cost from fuel switching to comply with it.

More specifically, the regulations define the two-tiered reduction targets in terms of a percentage reduction (Z-factors) relative to a benchmark fossil fuel intensity, $G = 93.3$ gCO$_2$eq/MJ. (Here and throughout, all quantities and variables can vary over time so are indexed t, which we omit for neatness).

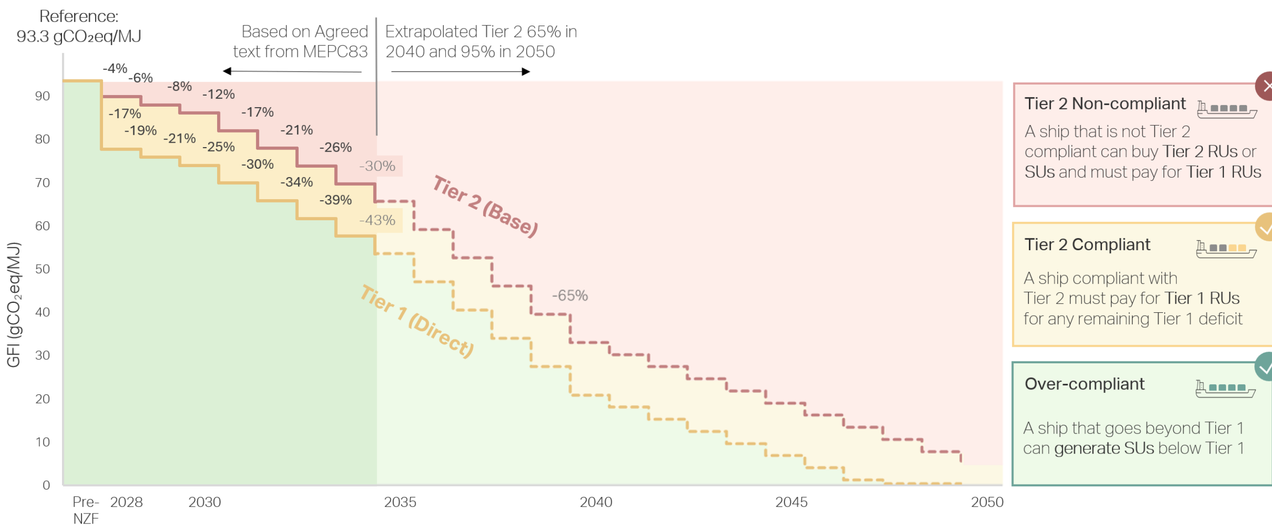
The mass of emissions above the rate-based limits are subject to penalties called "remedial unit" (RUs), denominated in a price per tonne of CO$_2$eq. Tier 1 is between the Direct and Base targets and sets a penalty of 100 USD per tonne of CO$_2$eq on a WtW basis. Tier 2 is above the Base target and sets a penalty of 380 USD per tonne of CO$_2$eq on a WtW basis. (The penalty rates will be reviewed periodically and may be adjusted).

The NZF also features "flexible compliance". This allows an RE to generate "surplus units" (SUs) for emissions that are below the Tier 1 limit ($e < e_D$). These SUs can be used by other REs to offset their liability for excess emissions above the Tier 2 limit ($e > e_B$), which would otherwise require the purchase of RUs.

As in other tradable performance standard regimes, flexible compliance enables REs that can minimize compliance costs more cheaply to offset the costs of those that cannot (for example, if only a subset of REs has access to a low-emission fuel).

Finally, the regulations include incentives ("rewards") for using specific fuels/energy/technologies, the so-called "zero or near-zero fuels" (ZNZs). These are payments for abatement achieved using ZNZs. ZNZ fuels are defined until 2034 as those with emissions of 19 gCO$_2$eq/MJ and below, and beyond 2034 of 14 gCO$_2$eq/MJ and below.

Figure 1: GHG Fuel Intensity (GFI) Reduction Factors (Z-Factors)



Note: 95% in 2050 is not part of the MEPC83 text and is an assumption. The direct compliance curve is also not defined post-2035. It is assumed that the 13% width is kept through 2050.
Source: *Countdown*: Historic IMO agreement lays groundwork for maritime decarbonization

1.2 Set up

The RE's total cost is the sum of underlying fuel cost(s), c and additional costs or rewards introduced through regulations. Here, fuel types are indexed by i (for example, fossil fuels or low-emission ZNZs):

$$\underbrace{C(\cdot)}_{\text{Total cost}} = \underbrace{\sum c_i \cdot q_i}_{\text{Fuel cost}} + \underbrace{P(\cdot)}_{\text{Regulatory costs / incentives}}$$

Regulatory cost or incentive drivers are functions of fuel-specific intensities, e_i, and the amount of fuel used (in energy units), q_i, using the *average* intensity of the fuel mix of the vessel, $e = (\Sigma_i e_i q_i)/(\Sigma_i q_i)$. These are converted to a total emission mass based on energy used $E = \Sigma_i q_i$.

The NZF sets piece-wise linear penalties or incentives as a function of the regulated entity's average overall emissions intensity. Put differently, the NZF imposes non-linear costs or incentives over the full solution space:

$$P(e) = \begin{cases} -s \cdot (e_D - e) \cdot E, & \text{if } e < e_D \quad \text{(SU)} \\ r_D \cdot (e - e_D) \cdot E, & \text{if } e_D \leq e < e_B \quad \text{(Tier 1 RU)} \\ r_B \cdot (e - e_B) \cdot E + r_D \cdot (e_B - e_D) \cdot E, & \text{if } e \geq e_B \quad \text{(Tier 2 RU and Tier 1 RU)} \end{cases}$$

Where s, r_D, r_B are Surplus Unit (SU) or penalty rates in cost per mass of emissions, for example USD/tCO_2eq. $P(e)$ is a cost or benefit as a function of the average intensity of the emissions e, and E, again, is the total energy used.

The two-tier GFS includes direct (Tier 1) and base (Tier 2) compliance targets, which we denote $e_D < e_B$. Emissions at intensities in the band between these limits are liable for the Tier 1 RU, r_D, and will not generate any Surplus Units. Emissions at intensities above the Tier 2 limit are also subject to the "full" cost of $r_D < r_B$, where r_B is the penalty imposed on excess emissions above the Tier 2 threshold $(e - e_B)$ and r_D is imposed on emissions in the band between the two tiers $(e_B - e_D)$.

Fuels $i \in \{\text{ZNZ}\}$ can secure rewards. Using Z for fuels meeting the ZNZ criterion, we can write the unit cost of this fuel as a function of the proportional difference between the fuel's emissions intensity and a reference intensity. Here, we use the reference intensity of fossil fuel,

$$c_Z = w_Z - [(G - e_Z) \cdot r_Z],$$

where w_Z is the fuel cost, G is the reference intensity (93.3 $\text{gCO}_2\text{eq/MJ}$), and r_Z is the reward rate denominated in cost per mass of CO_2eq, so c_Z is denominated in cost per unit energy.

Finally, in the flexible compliance framework, emissions below the direct compliance target (e_D) can be sold to non-compliant ships at a value per mass of emissions set by the rate s. We explain our model of how s is determined in section 4, below.

2 The RE's problem

The RE minimizes total costs. Under the NZF, these comprise direct energy (fuel) costs and the costs / incentives resulting from the regulatory framework. The is a price taker, so fuel and regulatory costs are exogenous.

Without loss of generality, we study the problem with $i \in A, F$: the regulated entity (RE) combines a higher-cost, lower-emission fuel, A, with a lower-cost higher-emission fuel, F, so $e_A < e_F$ and $c_A > c_F$. (We extend this to the case of A as a ZNZ fuel below). To ensure overcompliance is feasible, we assume $e_A < e_D$ and $e_F > e_B$. The RE's problem is to choose the energy demand from these fuels q_A, q_F. Setting total energy demand, E, to unity makes these shares of the total energy requirement.

$$\begin{aligned}
\min_{q_A, q_F} C = \quad & c_A q_A + c_F q_F + P(e) \\
\text{subject to} \quad & q_A + q_F = E = 1 \\
& e_A q_A + e_F q_F \leq \bar{e} \\
& e_A \leq \bar{e} \leq e_F \\
& q_A, q_F \geq 0
\end{aligned}$$

In words, the RE chooses q_A to minimize the sum of the cost of energy and the cost of regulations on emissions intensity above some limit, $\bar{e}$, while meeting the requirement for energy. Using $e = e_A q_A + e_F(1 - q_A)$ for emissions and $c_A q_A + c_F(1 - q_A)$ for costs, the standard Lagrangian is:

$$\mathcal{L}(q_A, \lambda) = c_A q_A + c_F(1 - q_A) + P\left(e\right) + \lambda \left[\bar{e} - \left(e_A q_A + e_F[1 - q_A]\right)\right]$$

The first order (stationarity) condition with respect to q_A is:

$$(c_A - c_F) + (e_A - e_F) \cdot \left[P'(e) - \lambda\right] = 0.$$

This can be usefully reorganized as

$$\lambda = \underbrace{P'(e)}_{\text{Marginal Regulatory Cost (MRC)}} - \underbrace{\frac{c_A - c_F}{e_F - e_A}}_{\text{Marginal Abatement Cost (MAC)}}$$

The first term is the cost of regulations as a function of total emissions. These can be either SUs generated, s, or costs avoided, r_D or r_B. We call this the marginal regulatory cost (MRC). The second term is the marginal abatement cost (MAC) from fuel switching. This is the cost per tCO_2eq of abating emissions.

The value of relaxing the intensity limit at some point e is the marginal regulatory cost imposed for emissions at that point, less the marginal abatement cost the RE would have needed to pay to be in compliance at that point.

Note that the function MRC $= P'(e)$ is piecewise linear:

$$P'(e) = \begin{cases} s, & \text{if } e < e_D \quad \text{(SU)} \\ r_D, & \text{if } e_D < e < e_B \quad \text{(Tier 1 RU)} \\ r_B, & \text{if } e > e_B \quad \text{(Tier 2 RU)} \end{cases}$$

Because the NZF allows Tier 2 deficits to be paid using surplus units, the cost of emissions in the region $e > e_B$ is generally $\min(s, r_B)$. This is the benchmark case for our solution in section 3, below.

2.1 Analysis

The RE can emit above an arbitrary intensity limit by internalizing the related cost, set by $P(e)$. Recall that for any given choice of e, λ is the value of emitting marginally more at this point. Because the constraint on emissions intensity, $\bar{e}$, is non-binding or "soft", we set $\lambda = 0$ and find the RE's optimizing choice of q_A using:

$$\lambda = 0 \rightarrow \text{MRC} = \text{MAC}$$

A given MRC = MAC is associated with a specific emission intensity, e^*. If this value minimizes the total cost function C, we can see the RE's optimal choices using the definition of e and $q_F + q_A = 1$:

$$q_F^* = \frac{e^* - e_A}{e_F - e_A}, \quad q_A^* = 1 - q_F^* = \frac{e_F - e^*}{e_F - e_A}.$$

This has associated fuel cost $c_F\, q_F^* + c_A\, q_A^*$. But because $P(e)$ is not convex, the values of e where $\lambda = 0$ need not be unique, so there can be multiple candidate solutions for the choice of e that minimizes total cost C. Put differently, a local minimum of the total cost function C may not be the global minimum.

2.2 Zero and Near-Zero fuels

The NZF specifies additional rewards to incentivize the uptake of so-called zero and near-zero (ZNZ) fuels and technologies.

While subject to clarification as regulations are finalized, it is expected that the reward for using a ZNZ fuel will be paid in proportion to the share of energy from these fuels and the amount of abatement generated, compared to a fossil fuel baseline (93.3 gCO_2eq/MJ).

The unit cost of a ZNZ fuel then becomes a function of its fuel cost less the fuel-specific reward. This lowers the marginal abatement cost of using a ZNZ fuel by reducing its net cost (the numerator of the MAC) without changing its abatement potential (the denominator of the MAC): $\partial \mathrm{MAC}_Z / \partial r_Z < 0$. The reward enters as a cost shifter and does not change the structure of the optimization problem, or the solution method presented below.[1]

3 Solutions

The RE's choices reflect regulatory penalties and market-based values, including s, the value of surplus compliance.

3.1 Solutions when $P'(e) = \min(s, r_B)$

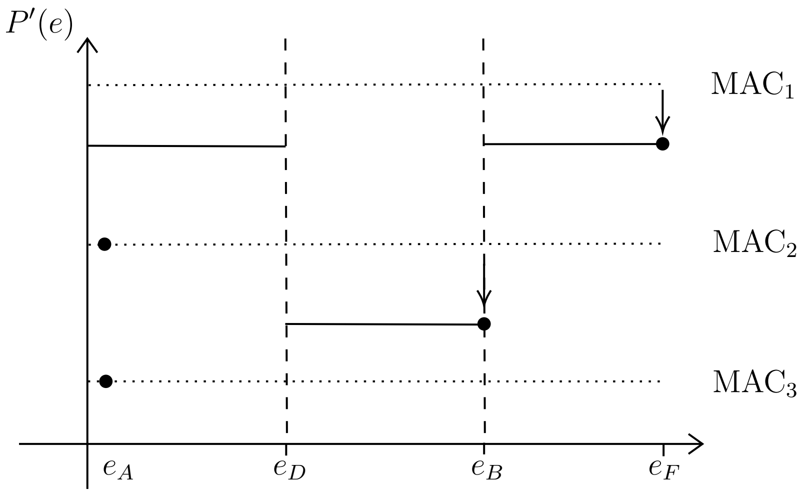
Offsetting the tier 2 compliance deficit can be paid with surplus units at a cost s or remedial units at a cost r_B. This means r_B is a price ceiling on s and, symmetrically, s is a ceiling on the cost of tier 2 compliance: for $e > e_B$, the marginal regulatory cost is $P'(e) = \min(s, r_B)$. Our benchmark case is therefore where these costs are the same: $s = r_B$ or $P'(e) = s \mid e > e_B$.

We examine a case with $e_A < e_D$, $e_B < e_F$ and, as before, $e_A < e_F$, $c_A > c_F$ and $r_D < r_B$. In other words, RE has access to abatement by using a lower intensity and higher cost alternative fuel, A, and the intensities of the fossil fuel, F, and this alternative fuel are, respectively, above and below the upper and lower tiers.

[1] This implicitly assumes the market for ZNZ fuels is perfectly competitive, so producers do not capture any share of the demand subsidy. Relaxing this assumption would affect the value of the MAC from ZNZs but not the underlying optimization problem we explore here.

Allowing the marginal abatement cost (MAC) to vary shows the set of candidate solutions. For any given MAC, there may be multiple candidate solutions because, as set out above, the regulatory cost function $P(e)$ is non-convex (it is piecewise linear).

Figure 2: RE's optimizing choices, when $s = r_B$ or $P'(e) = \min(s, r_B)$



Note: Markers indicate candidate solutions (i.e., emissions intensities e^*) where marginal abatement cost (MAC) equals marginal regulatory cost (MRC). Multiple equilibria arise due to the non-convexity of the regulatory cost function $P(e)$. Horizontal dotted lines correspond to different MAC levels. Arrows indicate solutions where the optimal behavior is driven by the regulatory cost(s) rather than abatement.

Specifically, if the MAC is above (MAC$_1$) or below (MAC$_3$) the MRC across the range of available intensities $e_A \leq e \leq e_F$, there is a single (unique) solution: the corner solution of zero abatement or maximum abatement.

If MAC < MRC in at least one section, there may be multiple potential solutions. We minimize the total cost $C(e)$ using the cost-minimizing value from e^* from among the candidate solutions.

	Case	$\mathbf{e}^*$
MAC$_1$	MAC $> s, r_D, r_B$	$e^* = e_F$ (no abatement: $q_A^* = 0$)
MAC$_2$	$r_D <$ MAC $< s, r_B$	$e^* = e_B$ (base target) or $e^* = e_A$ (max. abatement)
MAC$_3$	MAC $< s, r_D, r_B$	$e^* = e_A$ (max. abatement: $q_A^* = 1$)

Note: in the specific case where MAC $= s, r_B, r_D$, multiple candidate solutions may exist in some range: if MAC $= s, r_B$ then $e^* \in [e_B, e_F]$; if MAC $= r_D$ then $e^* \in [e_D, e_B]$.

3.2 Solutions when $e_F < e_B$

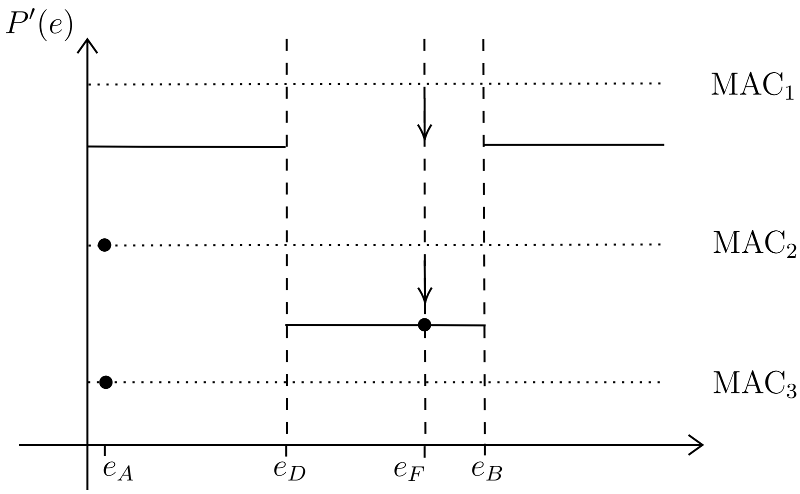
An important case is if there is some fuel F that has a lower intensity than the base target but higher than the direct target in a given period[2]: $e_D < e_F < e_B$. (Recall that the targets

[2]Under benchmark assumptions of the calculating tool discussed in section 5, below, this is the case for LNG, for example.

are implicitly indexed t because they reduce over time).

If the available MAC is above r_B and r_D, this is equivalent to the case of MAC_1, above, implying $e^* = e_F$ and hence $q_A^* = 0$.

Figure 3: RE's optimizing choices, when $e_F < e_B$ and $s = r_B$ or $P'(e) = \min(s, r_B)$



Note: Markers indicate candidate solutions (i.e., emissions intensities e^*) where marginal abatement cost (MAC) equals marginal regulatory cost (MRC). Multiple equilibria arise due to the non-convexity of the regulatory cost function $P(e)$. Horizontal dotted lines correspond to different MAC levels.

In words, the candidate optimal choice e^* is no abatement: it may be cost minimizing to pay the penalty rate $(e_F - e_D) \cdot r_D$. This is the benchmark case for scenario S_2 set out in section 5, below.

4 Surplus units

Under a flexible compliance mechanism, an RE that emits below the tier 1 (direct) target ($e < e_D$) can monetize the value of this "surplus" by selling these unused emissions to tier 2 (base) non-compliant vessels (those with $e > e_B$).

To model the value of SUs, we use a "market clearing" condition: the maximum willingness to pay for SUs is set by the marginal cost of compliance in the market.

We define MAC_i as the marginal cost of abatement using fuel i relative to a baseline fossil fuel F, for example:

$$\text{MAC}_A = \frac{c_A - c_F}{e_F - e_A}.$$

There may be a range of fuels available for abatement, comprising the the membership of i.[3]

[3] For example, $i \in \{\text{Biodiesel, Biomethane, ZNZ}\}$.

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 $e < e_D$) up to the maximum price of the Remedial Unit, r_B.

Below, we explain how the market for abatement sets this price. As successively cheaper abatement options are used, this raises the cost of surplus units and, equivalently, the value of generating this abatement using fuels below the tier 1 limit.[4]

4.1 Demand for surplus units

We put structure on the market for abatement to find s, the market-clearing price of the SU[5]. When fuel intensity calculations are made, a ship that has used fuel i with intensity below the Tier 1 GFI limit generates a mass of surplus emissions ("abatement") from that fuel if her average intensity, e, is below the lower Tier 1 cutoff:

$$Q_i^S = (e_D - e_i) \cdot E_i \quad \text{with} \quad e < e_D, e_i < e_D$$

where e is in mass CO_2eq per unit energy (for example, gCO_2eq/MJ) and E_i is energy used from fuel i, so Q_i^S is the mass of surplus generated. Then the total abatement available to the market from fuel i is the sum of abatement from this fuel across the regulated fleet. Indexing ships with h, this is:

$$\sum_{h=1}^{H} Q_{ih}^S = Q_i^A$$

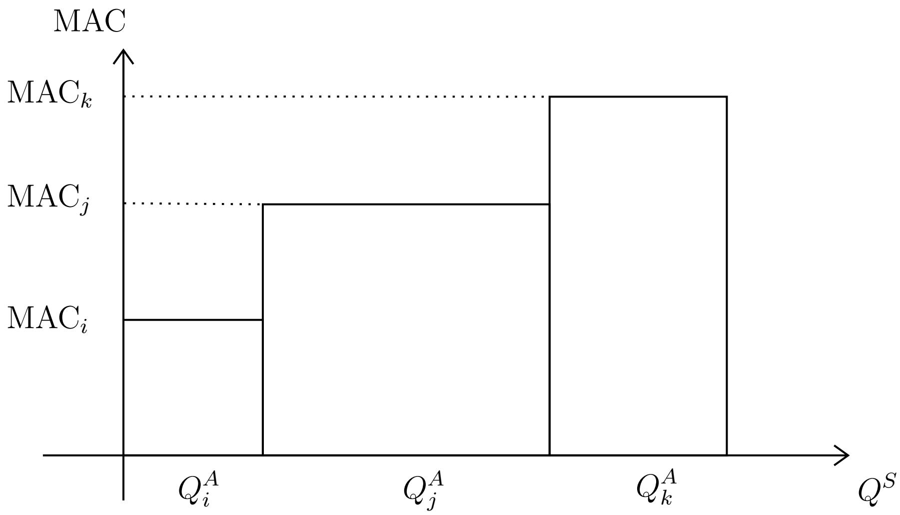
Similarly, when average intensity calculations are made, let Q^D be the demand for SUs, which is the sum of the mass of emissions from vessels whose average intensities exceed the Tier 2 GFI limit:

$$Q^D = \sum_{h=1}^{H} (e_h - e_B) \cdot E_h \quad \text{with} \quad e_h > e_B$$

where E_h is the sum of energy used by vessel h across all fuels i and e_h is the average emissions intensity of vessel h, so Q^D is measured in tons of abatement (demanded). Ordering fuels by their abatement costs MAC_i and abatement quantities Q_i^S in (MAC , Q^S) space renders the marginal abatement cost curve at time t:

[4] In markets for fuels for which shipping is not the marginal offtaker or consumer, the industry is a price taker; fuel prices may therefore be below the industry's willingness to pay, in this case set by the cost of penalties, providing abatement options below penalty costs. As these options are exhausted, the cost of compliance converges to the cost of the penalty.

[5] The NZF also allows SUs to be "banked" for up to two years, introducing intertemporal decision making to the RE's problem. Here, we focus on optimizing decisions in each period

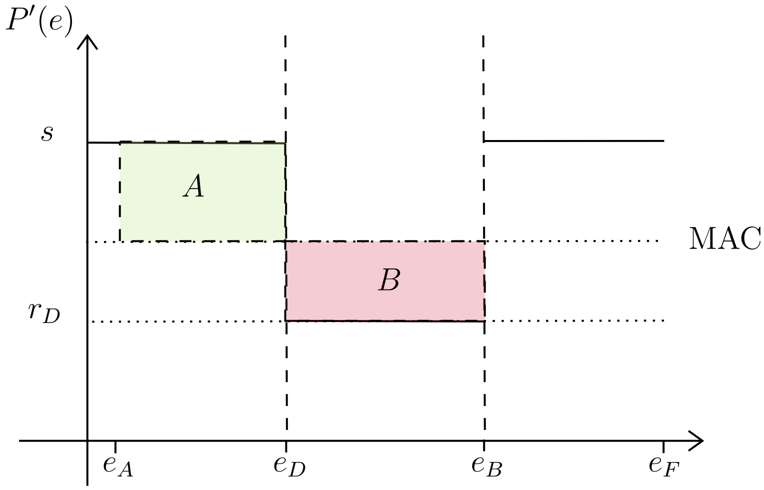


4.2 Market-clearing price of s

The market clearing MAC is lower than the market-clearing price of a Surplus Unit. This arises because the cost of available abatement options is generally above the lower Tier 1 penalty rate, r_D. Specifically, for some fuel with intensity $e_F > e_B$, an RE with access to MAC that is cheaper than the more expensive Tier 2 penalty will choose to abate to e_B. But to reduce below the lower Tier 1 limit, the RE must internalize the excess cost of abatement, relative to the Tier 1 penalty, in the range (e_B, e_D) to generate SUs in the range (e_A, e_D). This sets a lower bound on the break-even value of s for which the RE will choose $e^* = e_A$ below the Tier 1 limit:

$$(e_D - e_A)(s - MAC) \geq (e_B - e_D)(MAC - r_D)$$

In words, the term on the left is the value to the RE for abating below e_D (and so generating SUs). The term on the right is the added cost of abatement above the penalty rate r_D. (Recall that if s is large enough for the condition to be satisfied, the optimal choice is $e^* = e_A$). Visually, under the benchmark conditions $e_A < e_D$, $e_F > e_B$ and $r_D < MAC < r_B$, this is equivalent to requiring that s be large enough that the surface A is at least as large as surface B:

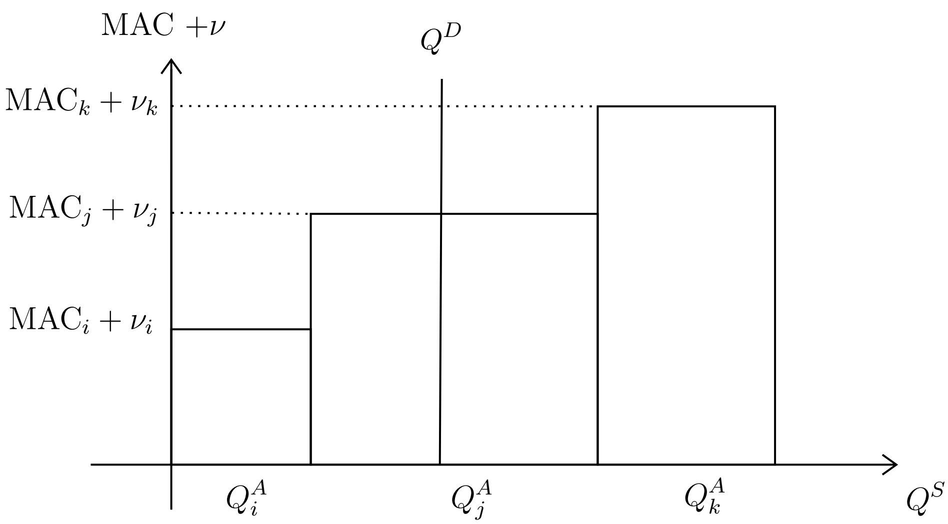


Reorganizing the break-even condition gives

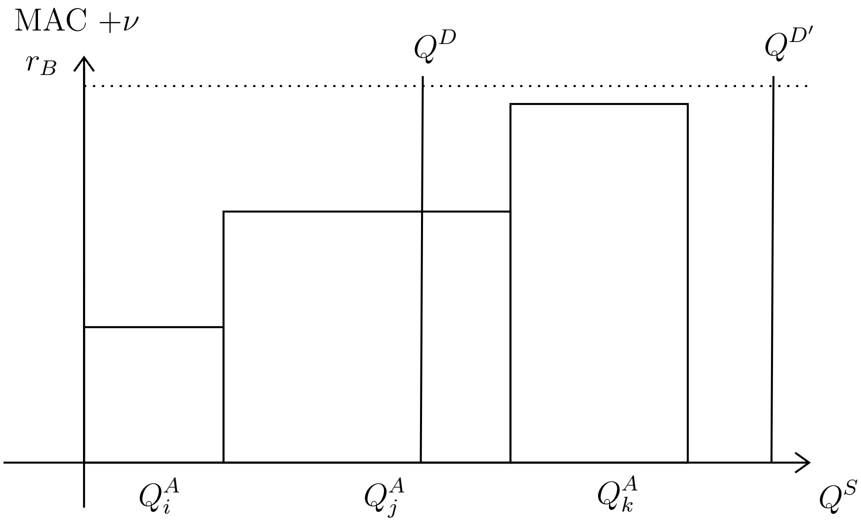
$$s \geq MAC + \frac{(e_B - e_D)(MAC - r_D)}{(e_D - e_A)} = MAC + \nu$$

This shows the cost of abatement above the Tier 1 rate raises the break-even cost of s at which the RE will supply SUs to the market. This vertical shift is the extra cost internalized by the RE to abate in the interval (e_B, e_D), added to each unit of s she generates over (e_D, e_A), denoted ν for neatness. The value of ν increases in the MAC, is positive under the benchmark configuration of $MAC > r_D$ and $e_A < e_D$, and decreases in r_D (because the greater this penalty rate, the smaller the extra cost of abating in the interval between the Tier 1 and Tier 2 intensities).

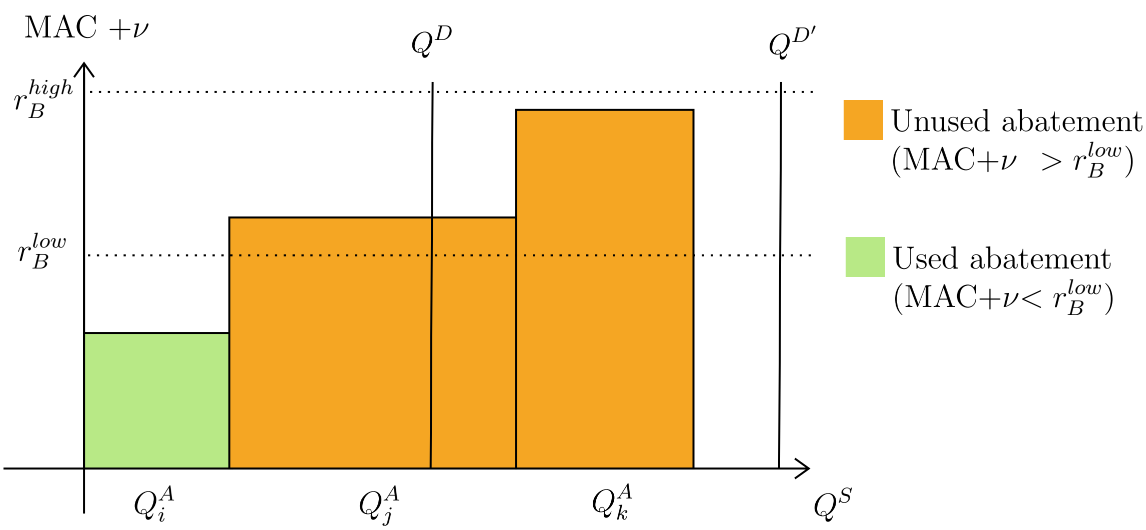
The market clearing price of the SU is then simply the cost $(MAC + \nu)^*$ associated with the marginal unit of abatement required, given the level of demand Q^D:



Returning to the market-wide demand, 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 the remedial unit (RU). Using $Q^{D'}$ for this level of demand (which exceeds available supply of abatement, or Surplus Units):



This underlines the criticality of the cost of the RU. 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. If the RU price is lower than some abatement cost MAC_i, then this fuel i cannot monetize its emission reductions because it is cheaper to pay the penalty:



5 Cost calculator

The NZF Fuel Cost Calculator ("Calculator") shows the impact of NZF regulations using a range of assumptions, including fuel costs and emissions intensities. These assumptions will be updated as regulations are finalized. The calculator includes sources for all assumptions and is user-editable. It can be downloaded here.

The calculator determines total costs, C, across four "strategies", S. Each strategy corresponds to a subset of fuels and constraints on the solution space for e. The set of strategies modeled are equivalent to the RE making the optimizing (cost-minimizing) choice between "no abatement" and abatement (through fuel switching) to avoid the costs of a compliance deficit, or "full abatement" using a ZNZ. This is equivalent to calculating total cost C for each candidate solutions identified above. The RE's optimal choice is then the candidate solution that minimizes the total cost.

- S_1: Using LSFO and the lowest cost between blending bio-diesel or paying the tier 2 RU. The total cost of this strategy includes the cost of the fossil fuel and the least costly option to offset the tier 2 compliance deficit.
- S_2: Using LNG and the lowest cost between blending bio-methane or paying the tier 2 RU. This is the same cost structure as strategy 1 using different fuels.
- S_3: Using LSFO and the lowest cost between ZNZ, and paying the tier 2 RU.
- S_4: Using 100% ZNZ-fuels, earning ZNZ rewards, and monetizing the value of excess compliance from selling SUs.

The tool is not designed to show the full range of compliance possibilities by default, but allows users to update assumptions on fuel costs, intensities, and regulatory variables. This flexibility allows users to simulate the effect of many fuel types and costs, in various combinations of interest. The default fuels and scenarios are included as likely strategies for compliance through fuel switching.

Specifically, strategies 1 through 3, (S_1, S_2, S_3), define a $\text{MAC}_{F,A}$ where F is a fossil fuel / gas and A is an alternative fuel or ZNZ. The RE evaluates $\text{MAC}_{F,A} \lesseqgtr r_B$ to choose among the candidate solutions. S_4 shows the effect of full abatement using a ZNZ:

	Fossil fuel F	Alternative fuel A	Solution range $e^* \in$
S_1	LSFO	Biodiesel	$(e_B,\, e_F)$
S_2	LNG	Biomethane	$(e_B,\, e_F)$
S_3	LSFO	ZNZ	$(e_B,\, e_F)$
S_4	–	ZNZ	e_A

Surplus Units (SUs) are not included as a way to offset the tier 2 deficit. Under benchmark cost assumptions, Biodiesel would set the lowest market cost for SUs in the tool's assumption set, so the strategy that includes LSFO and Biodiesel is the lower bound on total cost using SUs.

5.1 "Strategies"

The calculator applies constrained optimization to show costs C across the scenarios:

S_1: Blend biodiesel

The calculation of strategy 1 directly applies the framework above, with $F = \text{LSFO}, A = \text{Biodiesel}$, constrained to testing in the segment $e \geq e_B$. If $\text{MAC}_{F,A} \leq r_B$ the calculation shows $C(e_B)$. If $\text{MAC}_{F,A} > r_B$ then the calculation shows $C(e_F)$. Selecting the option to only use LSFO shows $C(e_F)$.

S_2: Blend Biomethane

The calculation is as in S_1, now with $F = \text{LNG}, A = \text{Biomethane}$.

Note that under benchmark assumptions, $e_F = e_{\text{LNG}} < e_B$ in some periods (ref. figure 3). This implies $q_F = 1$ and $e^* < e_B$, with a total cost (per unit energy) of

$$C = c_{\text{LNG}} + r_D \cdot (e_{\text{LNG}} - e_D)$$

in some periods. In words, the emissions intensity of the fossil gas may be low enough that a "no abatement" solution is optimal.

As regulations tighten over time ($e_{D,B}$ decrease), we have $e_F > e_B$. In these periods, the calculator again evaluates $\text{MAC}_{F,A} \lesseqgtr r_B$.

S_3: Use ZNZs

Strategy 3 has $F = \text{LSFO}, A = \text{ZNZ}$. The RE can combine fossil fuel with a ZNZ and earn a ZNZ reward factor. This strategy can have a corner solution as above, $q_F = q_{\text{LSFO}} = 1$ or $q_A = q_{\text{ZNZ}} = 1$. The calculator evaluates $\text{MAC}_{\text{LSFO,ZNZ}} \lesseqgtr P(e_B)$. 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

$$C = c_{\text{LFSO}}\, q^*_{\text{LFSO}} \;+\; c_{\text{Z}}\, q^*_{\text{Z}} \;+\; P(e, s, r_D)$$

where $c_{\text{Z}} = w_{\text{Z}} - \big[(G - e_{\text{Z}}) \cdot r_Z\big]$, the cost function for ZNZ-driven abatement including the reward rate r_Z. This strategy could imply tier 1 compliance by purchase of r_D.

S_4: Combining Surplus Units and ZNZ Rewards

Strategy 4 has $i \in \{\text{ZNZ}\}$ so enables the case of using only the ZNZ, implying $e^* = e_A$ so $q^*_{\text{A}} = q^*_{\text{Z}} = 1$. This approach "earns" the combined value of surplus units and ZNZ rewards. Since $e_{\text{Z}} < e_{D,B}$ in most periods/years, this strategy can generate incentives:

$$C = c_{\text{Z}} \cdot (q_Z = 1) \;+\; P\big(e_{\text{Z}}, s\big),$$

where the ZNZ reward is included in the fuel cost c_{Z}.

6 Version control

Subject to continuous edits and improvements; please use the most recent vintage. This version: `v2.1`. The authors are grateful to multiple reviewers (listed below) and are responsible for any remaining errors.

7 Authors: `v2.1`

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For `v1`, we are thankful to the following reviewers: Jenny Ruffell Smith, Joe Bettles, and Boudewijn Pragt.

For `v2`, we are thankful to the following further reviewers: Alfred Thorhauge Holbech, and Boudewijn Pragt.

For `v2.1`, we are thankful to the following further reviewer: Octave Pignet.

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