

Leakage, hold-up, and arbitrage in RED III maritime fuel policy

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Motivation

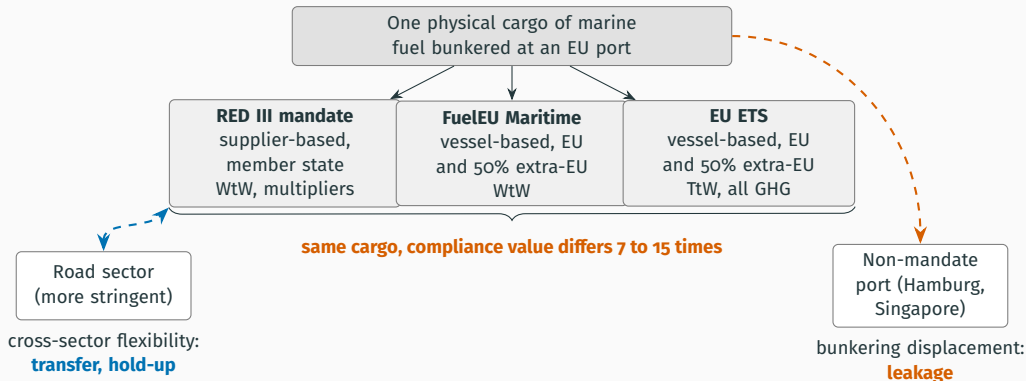
No global carbon price for ships yet

- In October 2025 the UN shipping agency voted to **postpone by a year** its decision on a global carbon price for ships (Reuters 2025)
- Shipping carries about 90% of world trade and emits nearly 3% of the world's CO₂ (Reuters 2025)
- Until a global price exists, the price signal for cleaner marine fuel comes from **regional rules**; in Europe, from three EU instruments that apply to the **same tonne of fuel**
 - RED III obliges the **supplier** that sells the fuel
 - FuelEU Maritime and the EU ETS oblige the **ship** that burns it

Question

Do these three instruments work together? The paper finds that they **often do not**.

One cargo, three instruments, three perimeters



Notes: Schematic after the paper's regime figure; FuelEU Maritime valued at its penalty. WtW: well-to-wake; TtW: tank-to-wake.

RED III framework

Three frictions, one question

Friction	What happens	Enters the model as
Leakage	A ship avoids the supplier's obligation by bunkering at a port where it does not apply	Retention $\mathcal{R}(\bar{\tau})$
Hold-up	A producer deciding today whether to build a fuel plant cannot tell which value its fuel will earn	Contractible share $1 - \beta$, enforcement q , hurdle multiple $w(\zeta)$
Arbitrage	A buyer can pick the fuel that the rules value most, which need not be the fuel that cuts emissions most	Value ratio Ω_i , fuel choice, fraud exposure

- Each friction arises where the directive's **design perimeter is narrower than the market**
- The model gives the direction of each effect and when investment fails. Whether the weakened signal still clears the hurdle is an **empirical question that the paper frames and does not resolve**

Link-by-link chains

Preview of results

- **Compliance value:** with FuelEU Maritime at its penalty, one cargo's value differs 7 to 15 times across the three instruments, mostly because they price a tonne of CO₂e differently
- **Per tonne abated**, bio-LNG and e-methanol are valued within 1% of each other (FuelEU at its penalty, without e-methanol's reward factor): differences between fuels come mostly from **chosen support**
- **Leakage:** after the Dutch mandate began, Rotterdam bunker sales fell by about a quarter while port calls barely changed; **consistent with** leakage
- **Investment:** narrow jurisdiction, weak enforcement and road-sector trading each cut the premium a producer can count on; uncertainty raises the return needed
- **Five corrections:** an obligation that follows the voyage, guaranteed compliance values, a binding RFNBO sub-target, fraud monitoring, common accounting

The port check is descriptive (one treated port, two quarters); the investment table is a map of the condition, not a calibration.

Related literature and contribution

1. **Instruments for shipping:** vessel-based instruments, leakage, overlapping carbon prices (Kotzampasakis 2025; Kotzampasakis and Wooley 2025; Cret et al. 2024; Dominioni and Petit 2025; Lehmann et al. 2025); market-based measures (Lagouvardou, Psaraftis, et al. 2022; Psaraftis et al. 2021); a practitioner survey records member states' choices, not whether together they work (Bureau Veritas Marine & Offshore 2026)
2. **Investment in green shipping:** real options, financing, charter contracts (Acciaro 2014; Metzger and Schinas 2019; Rehmatulla and Smith 2015; Mäkitie et al. 2022). There the investor is the **shipowner**; here, the **fuel producer**
3. **Theory:** leakage under incomplete regulation (Fowlie 2009; Markusen et al. 1995); the standard as implicit tax and subsidy (Holland 2012); trading across sectors (Fischer and Newell 2008; Long et al. 2025); hold-up (Williamson 1985); option value (Dixit and Pindyck 1994)

Four contributions

(i) Leakage from Germany's maritime exclusion and Spain's national-only scope, not analysed before for RED III; (ii) cross-sector trading as a transfer lenders cannot count (hold-up); (iii) the 7-to-15 value ratio from regulatory parameters and published prices; (iv) a model of the effective price signal under a fragmented mandate.

Closest estimates (1) (2)

Setting

Five member states, five designs; only the Dutch one adopted by April 2026

	Netherlands	Belgium	Germany	France	Spain
Mandate type	GHG intensity	Renewable share	GHG intensity	GHG intensity	GHG intensity
Maritime scope	Nat'l, int'l, inland	Nat'l, int'l	Excluded	Nat'l, int'l	National only
Cross-sector flexibility	Inward capped; outward to inland only	Maritime ↔ road	Road only	Within sector	Within party only
2030 GHG reduction	8.2%	≈14.9% ^a	n.a.	6.0%	10.0% ^b
Status, April 2026	Act adopted	Draft	Draft	Partial	Draft

Notes: Paper's mandate table, trimmed. ^a A 16.4% renewable share converted by the source; fuel mix, multipliers and WtW boundary behind the conversion not disclosed. ^b National shipping only. Source: Bureau Veritas Marine & Offshore (2026).

Other design margins Calendar

Mandate cost: a benchmark of EUR 18 to 22 per tonne of fuel oil in Rotterdam

1,000 t of fuel oil, 2026	Rotterdam	Antwerp	Hamburg	Le Havre	Barcelona
Maritime mandate in 2026	2.9% GHG reduction	7.2% renewable share	None	None yet	None yet
Obligation	110.4 tCO ₂ e	2,916 GJ renewable energy	0	0	0
Cost per tonne of fuel oil	EUR 18.2–22.1	Not priced	0	0	0

Notes: Paper's mandate-cost table, trimmed; an analytical illustration, not a legal determination. Dutch cost: obligation × the maritime credit price of EUR 165–200 per tCO₂e (lowest and highest weekly price, September 2026), a single-price benchmark.

- **Rotterdam:** EUR 18,216 to 22,081 for the cargo if the supplier passes the cost on in full; **Hamburg:** no obligation. A vessel moves its purchase when the detour costs less
- Up to 1.1 of the 2.9 percentage points can be met with road and inland units: more than a third of the obligation without sustainable marine fuel

More on mandate costs

Model

One inequality: the premium that survives must clear the hurdle

RFNBO capacity is built only if

$$\underbrace{q}_{\text{enforcement factor}} \times \underbrace{(1 - \beta)}_{\text{contractible share}} \times \underbrace{\mathcal{R}(\bar{\tau})}_{\text{retention}} \times \underbrace{\rho^*}_{\text{standalone premium}} \geq \underbrace{w(\zeta)}_{\text{hurdle multiple}} \times \underbrace{\frac{I}{y}}_{\text{capital intensity}}$$

- Three **haircuts** scale down ρ^* , the premium a standalone maritime mandate would pay under full enforcement
- The premium that survives must cover the plant's capital cost per unit of output, marked up for uncertainty: $w(\zeta) \geq 1$ rises with the volatility of project value

Design margin	Term	Rec.
Supplier-based jurisdiction	$\mathcal{R}(\bar{\tau})$	R1
Non-binding sub-target	q	R3
Road increment not counted by lenders	$1 - \beta$	R2
Uncertainty over rule revision	$w(\zeta)$	R2

Environment

Value chain

Machine-checked proofs

Leakage

Leakage: a mandate delivers abatement only on the volume it retains

- A supplier-based mandate is an **implicit tax** on fossil fuel and an **implicit subsidy** on sustainable fuel (full pass-through is the benchmark)
- Fuel at mandate port H costs the **wedge** $\bar{\tau}$ more than at port A (no obligation); a vessel bunkers at H only if its detour cost $\delta \geq \bar{\tau}$
- Retention $\mathcal{R}(\bar{\tau}) = 1 - G(\bar{\tau})$ falls with stringency

Net abatement equals retention

$$\mathcal{A}^{\text{net}} = \mathcal{R}(\bar{\tau}) \times Q \times (g_f - \sigma)$$

$$\eta \equiv \frac{\mathcal{A}^{\text{net}}}{\mathcal{A}^{\text{int}}} = \mathcal{R}(\bar{\tau})$$

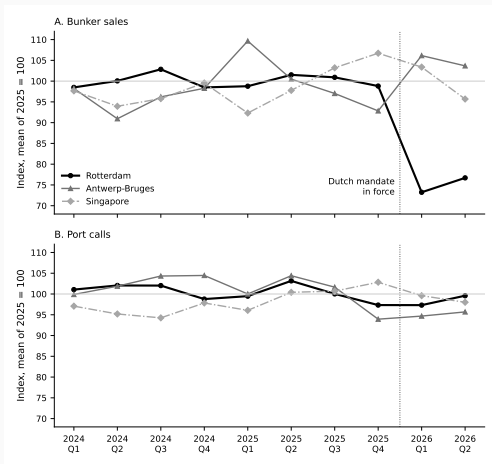
Leakage cuts net abatement and the demand producers can sell into.

Notes: Q : regional bunker demand; $g_f = 94 \text{ gCO}_2\text{e/MJ}$; σ : the standard.

Formal results

Overlap with vessel-based rules

Rotterdam bunker sales fell by about a quarter; port calls did not



- **Rotterdam sales:** −25.9% in 2026 Q1 and −24.4% in Q2, on a year earlier; through 2025 they moved by less than 2% a year
- **Rotterdam port calls:** −2.2% and −3.5%
- Antwerp-Bruges sales: −3.2% and +3.2%; Singapore: +12.0% and −2.1%
- Vessels kept calling but bought less fuel there: the pattern the model predicts, **although the data do not follow vessels or show where fuel was bought**

Notes: Paper's leakage figure. Series set to 100 at their 2025 mean; A: bunker sales (port authorities); B: port calls (IMF PortWatch). Dotted line: January 2026.

Table of changes

The Rotterdam check is descriptive, with one treated port and two quarters

Rotterdam relative to comparison ports (%)	Both ports	Singapore alone
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Bunker sales	−28.0	−25.9
Port calls	0.7	−2.8
Sales per call	−28.5	−23.8

Reading it as retention

If the whole fall is leakage, a wedge of EUR 16.6 to 18.2 per tonne (first-week-of-January credit prices, full pass-through) retained about **72%** of bunker volume: a benchmark, not an identified point on the retention curve.

Limits stated by the paper

- No standard errors (not informative); placebo estimates range from −4.0% to 1.7%, against −28.0% at the true date
- The data do not show where vessels buy fuel; other causes cannot be ruled out; a vessel-level estimate remains to be done
- The comparison ports may receive part of the fuel, in which case both estimates overstate the fall
- The war between the United States and Iran disrupted markets; the second quarter is the less clean of the two

Data and timing

Hold-up

Hold-up: a road link adds a transfer that a lender cannot count

1. In the Belgian and Spanish drafts, maritime credits within the cap earn the **road price**; the state can close the route, as the Netherlands did with the HBE transfer
2. When suppliers pass part of the road value to operators as a **discount** (a share λ), an operator offers less for a long-term offtake
3. A lender counts only what the state cannot revise: the **road increment is excluded**; the premium may fall short of the hurdle

Linkage substitutes a transfer for a contractible signal

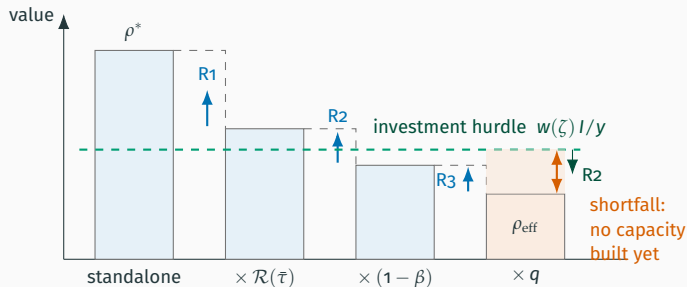
$$\rho_{\text{eff}} = q(1 - \beta) \mathcal{R}(\bar{\tau}) \rho^*$$
$$\beta = \min \left\{ 1, \frac{\lambda (p^R - p^M)}{q p^M} \right\}$$

$p^R > p^M$: road and maritime credit prices.
Without a commitment, $\beta > 0$ whenever $\lambda > 0$; without a link, $\beta = 0$. If the state commits to keep the route open for the loan term, $\beta = 0$ (R2).

Hold-up by a regulator that can change the rules after capital is sunk.

Derivation Welfare

Three haircuts cut the premium below the hurdle



Notes: After the paper's cascade figure; bar heights are schematic.

- A frictionless mandate finances capacity: the standalone premium sits **above** the hurdle
- R1 raises retention; R2 lowers the hurdle and, through its route commitment, raises the contractible share; R3 makes enforcement more likely
- The RFNBO sub-target says “shall endeavour”: no enforceable obligation

Frictions multiply: the financed capital intensity shrinks with each

Combined haircut h	Scaled volatility $u = \zeta^2 / (2r)$					
	0	0.10	0.25	0.50	1.00	2.00
Hurdle multiple w	1.00	1.37	1.64	2.00	2.62	3.73
$h = 1.00$	1.00	0.73	0.61	0.50	0.38	0.27
$h = 0.90$	0.90	0.66	0.55	0.45	0.34	0.24
$h = 0.75$	0.75	0.55	0.46	0.38	0.29	0.20
$h = 0.50$	0.50	0.36	0.30	0.25	0.19	0.13
$h = 0.25$	0.25	0.18	0.15	0.12	0.10	0.07
$h = 0.10$	0.10	0.07	0.06	0.05	0.04	0.03

Notes: Paper's investment table. Cells: index $a = h/w$, the largest I/y at which a project is built, as a share of ρ^* ; first row: hurdle multiple w ; $h = q(1 - \beta)\mathcal{R}(\bar{\tau})$. A grid, **not a calibration**.

- Financed capital intensity is **proportional** to each haircut: the effects multiply
- If the rules alone raise u from zero to 0.25: $w = 1.64$, and a mandate with **no haircut** finances projects only up to **61%** of the benchmark capital intensity; with $h = 0.75$, 46%
- Removing the volatility the rules add (R2) would lift 61% to 100%: the most R2 can achieve through volatility
- At $u = 0.5$, $w = 2.00$: the textbook case (Dixit and Pindyck 1994; McDonald and Siegel 1986)

Option to wait Dated hurdles

Arbitrage

One cargo earns three values that differ 7 to 15 times

	B30 blend	Bio-LNG	E-methanol (RFNBO)
<i>Compliance value relative to fuel oil (EUR/Gj)</i>			
RED III, Dutch maritime mandate	0 ^a	13.7	12.0
FuelEU Maritime	14.3	40.1	96.5
EU ETS	2.0	5.7	6.6
Sum across instruments	16.3	59.6	115.1
Value ratio: highest to lowest instrument	7.2	7.0	14.6
<i>Combined value per tonne of CO₂e abated (EUR)</i>			
FuelEU Maritime at its penalty	707	923	1,811 (914)
FuelEU Maritime at 25% of its penalty	241	457	672 (448)

Notes: Paper's compliance-value table, trimmed; in brackets, e-methanol without the reward factor. Prices: allowance EUR 84.49/t (September 2026 mean); Dutch credit EUR 182.5/tCO₂e (midpoint); FuelEU penalty EUR 638/tCO₂e, the ceiling of the FuelEU value, with reward factor 2 for the RFNBO. E-methanol at the highest intensity an RFNBO may have: its ratio is a lower bound. The ratios show how far valuations diverge, not a loss.

^a Annex IX Part B biodiesel cannot count toward the Dutch obligation.

Most of the gap is price; it narrows with a lower FuelEU value but does not close

- **Price:** a ship in deficit under FuelEU pays about EUR 638 per tonne of CO₂e, against an allowance price of EUR 84.49 (a ratio of 7.6)
- **Accounting:** the reward factor counts an RFNBO's energy twice, lifting the e-methanol ratio from 6.0 to 14.6
- Large per-tonne differences are **chosen support:** the reward factor adds 98% to e-methanol's value, RED III adds 30% to bio-LNG's
- Pooled FuelEU surplus traded at EUR 170 to 208 (market data), a quarter to a third of the penalty: ratios then fall toward 1.8 to 3.7

		Bio-LNG, engine			E-methanol	
Share	B30	Diesel	Otto S	Otto M	Reward	None
100%	7.2	6.9	7.0	7.2	14.6	6.0
75%	5.4	5.2	5.3	5.4	11.0	4.5
50%	3.6	3.4	3.5	3.6	7.3	3.0
25%	1.8	2.1	2.4	2.7	3.7	1.8

Notes: Paper's sensitivity table, Panel B: value ratio when the FuelEU value is a share of its penalty; allowance EUR 84.49; a grid, not estimates. The ratios are not a bound: the penalty caps the FuelEU value, not the ratio.

Allowance-price sensitivity

Accounting rules

Arbitrage runs mainly through fraud exposure

Case	Example	Status
(a) Concurrent recognition	Supplier counts the cargo under RED III; the ship under FuelEU and the ETS	Legitimate
(b) Duplicate claim	A second ship, or member state, claims the same record	Not legitimate
(c) Fabricated record	A false record presents fossil gas as biomethane	Not legitimate

- A false certificate earns the **sum** of the three values: EUR 59.6/GJ for bio-LNG, EUR 115.1/GJ for e-methanol (FuelEU at its penalty); under the ETS alone, EUR 5.7 and 6.6
- Removing multipliers need **not** remove the incentive: the certificate price alone can make a false claim pay
- The Union Database blocks reuse of biomethane certificates but does not verify the injection data behind them

Per tonne abated the unintended accounting gaps are small; arbitrage runs mainly through fraud.

Chain of custody

Fuel choice and fraud results

Recommendations

Five corrections, each tied to a term of the model

	Correction proposed	Acts on
R1	Close the jurisdictional gap on bunkering: extend RED III obligations to fuel sold to vessels that called at an EU port within the preceding 60 days	Retention $\mathcal{R}(\bar{\tau})$
R2	Publish binding compliance-value tables, guaranteed from the investment decision through lead time and first years of output; a road route open at financing stays open for the loan term	$w(\zeta); 1 - \beta$
R3	Make the 1.2% RFNBO maritime sub-target binding for member states with ports above a set bunkering volume, under an infringement procedure	Enforcement q
R4	Set up a cross-instrument fraud risk monitoring unit: link the Union Database and Thetis with ISCC and RSB, tying each claim to one cargo record	Duplicate and fabricated claims
R5	Unify GHG accounting across RED III, FuelEU and the ETS: boundary, warming potentials, fossil reference; support the legislator chose (reward factor, multipliers) stays	Value per tonne abated P_i

R5 is the lowest priority: the unintended accounting difference is small today; it protects against rules that diverge again on separate dates.

Legal routes and barriers set the sequence

	Legal route	Main barrier
R1	Amend the directive	Reaching fuel bought outside the EU raises a question of jurisdiction; a look-back window leaves gaps
R2	Commission regulation (tables); amend the directive (route commitment)	Tables fix the credited benefit, not the credit price: regulatory risk falls, price risk stays; the commitment ties member states' hands at reviews
R3	Amend the directive	Costly if RFNBO supply is not ready by 2030 (needs a phase-in); a volume threshold invites sales to move to smaller ports, so R3 works best with R1
R4	Regulation and coordination	Records sit with different bodies: sharing needs a legal basis and common identifiers; verification costs weigh most on small producers
R5	Delegated acts; amendments for the boundary and fossil reference	The ETS counts emissions where fuel is burned in every sector; a well-to-wake boundary would set shipping apart; new values need a transition period

Sequencing: R1, R3, the route commitment of R2 and the boundary and fossil-reference parts of R5 need the ordinary legislative procedure and take longest; the tables of R2 and R4 need only Commission acts and coordination, the warming potentials of R5 a delegated act. All should start before the current transposition review closes the window for design correction.

Conclusion

What the paper does not show

- The leakage estimate is **one port in two quarters**; retention should be higher at a port with no close neighbour and lower where ports cluster
- The model is deliberately simple (two ports, one fuel pair, inelastic demand, fixed ship speed); its structural parameters are **not estimated**
- The investment table is a map of the condition, not an estimate
- The value ratio holds at 2026 prices with FuelEU at its penalty, and changes as the FuelEU target tightens and the reward factor ends after 2033
- The linking result needs a road market with a higher credit price
- The model does not show that mutual waiting causes the supply gap

Open empirical questions

1. The price differential that moves bunkering to non-mandate ports
2. The investment shortfall due to regulatory uncertainty during transposition
3. How well the Union Database detects fraud once extended to maritime

The paper frames these without resolving them; their answers will decide whether the current design can meet the 2030 targets.

Conclusion

- RED III's **compliance perimeter is narrower than the market** it governs: the member state's border, the supplier's invoice, the relevant annex
- **Leakage**: ships can avoid the mandate within the law; the fall in Rotterdam's bunker sales is consistent with it
- **Hold-up**: compliance values cannot be contracted in advance, which weakens the incentive to invest
- **Arbitrage**: one cargo is valued 7 to 15 times differently across three instruments; today it runs mainly through fraud

Three overlapping instruments do not yet send producers one contractible price signal.

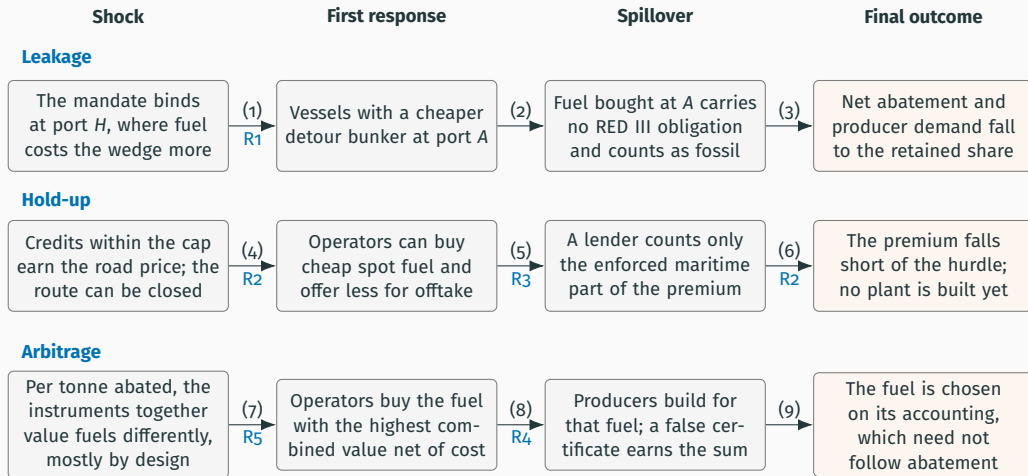
Thank you! hmorao@phd.iseg.ulisboa.pt

Backup

RED III framework and the maritime sub-target

- Each member state chooses between a **29% renewable energy share** and a **14.5% cut in the GHG intensity** of transport energy by 2030; a fuel can rank high under one and low under the other
- Biofuels and biogas count only if they meet Article 29: plants started in 2021 or later must cut lifecycle emissions by at least 65% against the 94 gCO₂e/MJ fossil reference; older plants by 50% or 60%; RFNBOs by 70%
- A **multiplier** m lets one MJ count as m MJ: each MJ earns more compliance units, and the supplier needs less physical fuel, so the mandate delivers less renewable fuel
- The maritime **sub-target**: member states with ports “shall endeavour” to reach a 1.2% RFNBO share of maritime energy by 2030, language that creates no enforceable obligation and no penalty
- Hydrogen projects take three to six years to develop (International Energy Agency 2025); an e-methanol plant two to three years to build (International Renewable Energy Agency and Methanol Institute 2021)

The three frictions, link by link



Notes: The paper's chains figure, redrawn; R1 to R5 mark the recommendation acting on each link.

Closest published estimates: leakage and compliance value

Study	Estimate	Against this paper
<i>Leakage</i>		
Fowlie (2009)	California electricity, 2004: incomplete regulation achieves about a third of the cut of complete regulation	Different measure, more leakage: output moves across the grid, at a carbon price several times higher
Banfi et al. (2005)	Swiss border petrol stations, 1985–1997: fuel tourism about 9% of sales in border regions	Same margin, smaller shift: a car tank lasts days, a ship's bunkers weeks
EUROCONTROL (2019)	European aviation, 2018: 16.5% of flights could profitably carry fuel for their next flight	Same margin; ReFuelEU now makes airlines uplift 90% of their fuel at each EU airport
<i>Compliance value across instruments</i>		
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2026)	First FuelEU compliance year: penalty about EUR 640 per tCO ₂ e; pooled surplus traded at about EUR 208 (2025 mean) and 170 (May 2026)	Same penalty; the market value is a quarter to a third of it, the low end of the sensitivity table
Lagouvardou, Lagemann, et al. (2023)	Supramax bulk carrier, new build: carbon price needed, bio-LNG USD 134 to 237, e-methanol USD 266 to 937 per tCO ₂ e	Most fuels need more than the allowance price and less than the FuelEU penalty

Notes: Condensed from the paper's appendix table of closest published estimates, which also gives setting and method.

Closest published estimates: investment hurdle and linking markets

Study	Estimate	Against this paper
<i>Investment hurdle and contractible share</i>		
Dixit and Pindyck (1994); McDonald and Siegel (1986)	Real options: invest when project value is twice the cost (base case)	Agrees: their cases have a scaled volatility of 0.5, where $w = 2.00$
Agnolucci et al. (2014)	Panamax time charters, 2008–2012: owners recover about 40% of the savings from energy efficiency	Analogue of the contractible share $1 - \beta$
<i>Linking markets</i>		
Long et al. (2025)	China's performance standard, 2020–2030: broader trading raises emissions by up to 10%	Neither finds a sure gain; other channel: allowance creation there, investment here
Fischer and Newell (2008)	US electricity: a renewables share requirement costs about twice an emissions price for the same cut	R3 rests on contractibility, absent from their model
<i>This paper, linking</i>		
	The transfer cancels; a static gain in the road sector against delayed maritime investment when $\lambda > 0$; either can be larger	

Notes: Condensed from the paper's appendix table of closest published estimates.

Other design margins of the five transpositions

	Netherlands	Belgium	Germany	France	Spain
RFNBO multiplier	None	2.0×	n.a.	None stated	None stated
Annex IX-B status	Excluded from maritime	Capped (0% non-advanced)	n.a.	Capped (tall oil, tallow)	Capped at 1.7%
Virtual liquefaction	Prohibited	Permitted	n.a.	Permitted	Permitted
Effective GHG intensity 2030 (gCO ₂ e/MJ)	≈86.3	≈80.0	n.a.	≈88.4	≈84.6
Implementation date	Jan 2026 (retro.)	Jan 2026 (retro., unconfirmed)	Road only, 2026	Jan 2027 (retro., unconfirmed)	Jan 2027 (retro., unconfirmed)

- In May 2025, 26 of the 27 member states missed the transposition deadline. The Dutch Act and decree entered into force on 20 June 2026 with effect from 1 January 2026
- Netherlands: up to 1.1 percentage points of the 2026 obligation (2.5 of 2030) may be met with road and inland units; the 2030 8.2% is a sector obligation of 5.7% plus a flexible allowance of 2.5%

Notes: Paper's mandate table, remaining rows. Sources: Bureau Veritas Marine & Offshore (2026); national legislation and drafts as of April 2026.

Calendar of the three instruments

Year	RED III and national mandates	FuelEU Maritime ^a	EU ETS ^b
2024	—	—	40% of emissions; CO ₂
2025	Transposition deadline, 21 May	2% reduction; RFNBO reward factor of 2 begins	70% of emissions; CO ₂
2026	Dutch maritime mandate applies, 2.9% reduction	2% reduction	100% of emissions; CO ₂ , CH ₄ , N ₂ O
2030	29% renewable share or 14.5% intensity reduction in transport; maritime RFNBO share of 1.2% (non-binding); Dutch maritime mandate at 8.2%	6% reduction	100% of emissions
2033	—	Last year of the RFNBO reward factor	100% of emissions
2035	—	14.5% reduction	100% of emissions
2040	—	31% reduction	100% of emissions
2045	—	62% reduction	100% of emissions
2050	—	80% reduction	100% of emissions

Notes: Paper's calendar table. ^a Required reduction in the GHG intensity of energy used on board, against 91.16 gCO₂e/MJ. ^b Share of verified emissions for which allowances must be surrendered, and the gases covered.

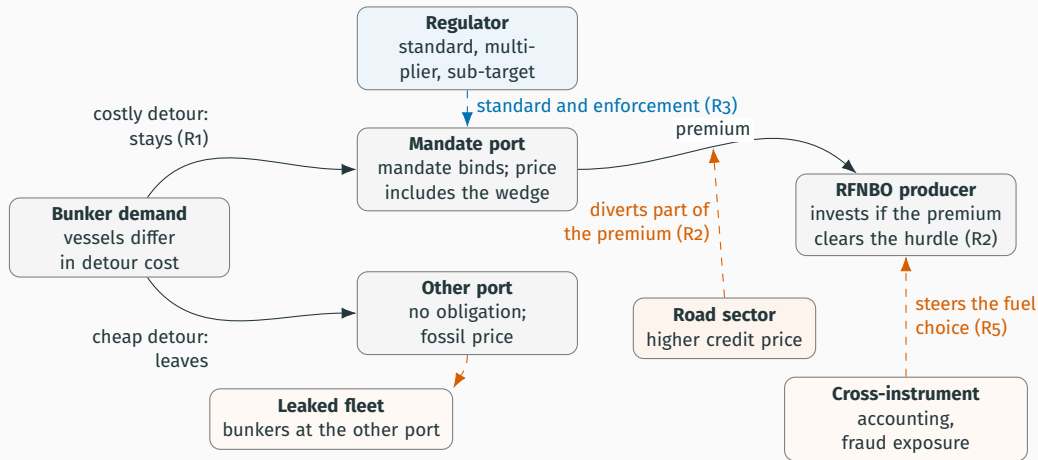
More on mandate costs

- **Dutch obligation:** reduction share $\times$ fossil comparator (94 gCO₂e/MJ) $\times$ energy content of fuel oil (40.5 GJ per tonne) = 110.4 tCO₂e per 1,000 t in 2026. At the 2030 obligation of 8.2%: 312.2 tCO₂e, EUR 51.5 to 62.4 per tonne at the same credit prices
- **Benchmark at January prices:** at the credit prices of the first week of January 2026 (EUR 150 to 165 per tCO₂e) the 2026 cost is EUR 16.6 to 18.2 per tonne of fuel oil
- **Belgium** (renewable share of 7.2%): 2,916 GJ of renewable energy per 1,000 t; with multipliers, 2,430 GJ of advanced biofuel or 1,458 GJ of RFNBO; without them, as biofuel at the minimum saving of 65%, 178.2 tCO₂e. No Belgian credit price is published; application to bunkering since January 2026 is unconfirmed
- **Observed price gap:** in February and March 2026 very low sulphur fuel oil cost about USD 14.50 per tonne more in Rotterdam than in Antwerp (Tassi Lara and Al-Khalisy 2026); another period and currency, and it does not identify pass-through

Model environment

- **Ports and fuels:** port H has a maritime intensity mandate, port A none (for example Germany, or Singapore). Fossil fuel f : intensity $g_f = 94 \text{ gCO}_2\text{e/MJ}$, marginal cost c_f . Sustainable fuel s : intensity g_s below the standard σ , higher long-run cost c_s ; $\Delta c = c_s - c_f > 0$
- **Demand:** Q megajoules, inelastic but mobile; each unit carries a detour cost δ from a continuous distribution G on $[0, \bar{\delta}]$
- **Pass-through:** obligated suppliers are perfectly competitive with constant marginal costs; compliance charges and credit values pass through one-for-one to delivered prices
- **Timing:** investment stage = the date a national transposition takes effect; market stage = the compliance period up to the 2030 targets, when the policy state (whether the sub-target is enforced) resolves. Revision of the rules continues, so it enters through the volatility of project value
- FuelEU Maritime and the ETS bind the vessel wherever it buys fuel, so they drop out of the choice of port

The model as a value chain



Notes: The paper's value-chain figure, redrawn: leakage, diversion and weak enforcement cut the premium before it meets the hurdle.

Machine-checked proofs

- The paper pairs each result with theorems in Lean 4 with Mathlib. The 101 theorems contain no `sorry` and are in the replication package (`Red3Proofs.lean`)
- The axiom audit reports Lean's three standard axioms and, for the endogenous-price equilibrium, a formalization of Brouwer's theorem from outside Mathlib
- **Coverage varies.** Full statement: share-intensity equivalence, basket cost, operator indifference, credit price, leakage ceiling, fraud. Main parts only: most other propositions. Arithmetic only: welfare decomposition, and the values of the compliance and mandate-cost tables
- **In prose only:** the $m > 1$ cases, the committed route in the linkage proposition, the delay statement in the main proposition. **Not checked:** the two limits in the option lemma, the decline past the maximum in the Laffer corollary, the finite-horizon convergence results. **Taken as given:** what a lender counts

Formal results: share, wedge, credit price, and the Laffer property

Basket and credit price ($m = 1$, interior)

$$\theta = \frac{g_f - \sigma}{g_f - g_s}, \quad \bar{\tau} = \theta \Delta c, \quad p^M = \frac{\Delta c}{g_f - g_s}$$

$$t_f = p^M (g_f - \sigma), \quad s_s = p^M m (\sigma - g_s)$$

Both θ and $\bar{\tau}$ rise with stringency. The credit price is the marginal cost of abatement by substitution; the basket at H costs $c_f + \bar{\tau}$, and a vessel bunkers at H iff $\delta \geq \bar{\tau}$.

Operators are indifferent

$$P_f = c_f + p^M (g_f - \sigma) = c_s - p^M (\sigma - g_s) = P_s$$

The supplier's obligation alone fixes θ .

Laffer property

$$\frac{\bar{\tau}^* \gamma(\bar{\tau}^*)}{1 - G(\bar{\tau}^*)} = 1$$

If $\Delta c \geq \bar{\delta}$, every maximizer of net abatement is interior, where retention is unit-elastic in the wedge.

Producers sell into $V_s = \theta \mathcal{R}(\bar{\tau}) Q$. Leakage ceiling: $\rho^* \leq \frac{m(\sigma - g_s)}{g_f - \sigma} G^{-1}(1 - \hat{\mathcal{R}})$ for a target retention $\hat{\mathcal{R}}$. With $m > 1$ the physical share falls to θ_m and the results carry over with θ_m in place of θ . With FuelEU Maritime binding the ship, effectiveness is still the retention rate, on a smaller base.

Overlap with the vessel-based instruments

- Let v^V be the value per MJ that FuelEU Maritime, the ETS and (as a shadow value) the CII give sustainable fuel relative to fossil fuel; the charge on fossil fuel is the same at both ports and cancels from the choice of port
- If $v^V < \Delta c$, the mandate binds, and

$$p^M = \frac{\Delta c - v^V}{g_f - g_s}, \quad \bar{\tau} = \theta (\Delta c - v^V), \quad \Delta c = v^V + \rho^* + \bar{\tau}$$

both decreasing in v^V , so **retention does not fall**

- If the vessel-based value escapes enforcement and diversion, the signal reaching producers is $\rho_{\text{eff}} = \mathcal{R}(\bar{\tau}) [v^V + q(1 - \beta)\rho^*]$, strictly increasing in v^V while retention is positive
- If $v^V \geq \Delta c$, the mandate does not bind, the wedge is zero, and there is no leakage

Notes: Overlap proposition (Extension F of the paper). Retention that does not fall with the wedge is taken as given in the proof.

Bunker sales and port calls: change on the same quarter a year earlier (%)

Quarter	Rotterdam			Antwerp-Bruges		Singapore	
	Sales	VLSFO	Port calls	Sales	Port calls	Sales	Port calls
2025 Q1	0.3	−1.9	−1.6	11.6	0.1	−5.5	−1.0
2025 Q2	1.5	−17.5	1.1	10.5	2.5	4.1	5.5
2025 Q3	−1.9	−14.9	−2.0	0.9	−2.6	7.7	6.8
2025 Q4	0.3	−2.5	−1.5	−5.5	−10.1	7.2	5.1
2026 Q1	−25.9	−40.0	−2.2	−3.2	−5.3	12.0	3.7
2026 Q2	−24.4	−33.2	−3.5	3.2	−8.3	−2.1	−2.4

Notes: Paper's appendix table of leakage data. Sales: total bunker sales in tonnes, fossil and bio-blended. VLSFO: very low sulphur fuel oil, bio-blended included. Port calls: calls of seagoing cargo vessels. The Dutch maritime mandate applies from January 2026. Sources: port authorities of Rotterdam and Antwerp-Bruges, MPA Singapore, IMF PortWatch; author calculations.

- Bio-blended sales in Rotterdam rose 44.2% in 2026 Q2; the data cannot attribute the rise to the mandate

Leakage check: data and timing

- **Timing:** the Dutch obligation covers fuel delivered from 1 January 2026, but the Act was published in April and the decree in May; both entered into force on 20 June 2026 with retroactive effect. First-quarter figures reflect a liability suppliers expected rather than one already in law
- **Sources:** quarterly bunker sales by the port authorities of Rotterdam and Antwerp-Bruges, monthly sales of the Maritime and Port Authority of Singapore, and daily port calls from IMF PortWatch, summed to quarters; window 2024 Q1 to 2026 Q2
- **Discrepancy in a source:** for 2026 Q1 the Antwerp-Bruges table gives 2.10 Mt in all, while the chart of the same release shows about 2.5 Mt. The table is used; with the chart's figure the estimate against both comparison ports would be -31.3% instead of -28.0% , and the Singapore-alone estimate is unaffected
- **Where fuel went:** market reports name Antwerp, Gothenburg and German ports (Tassi Lara and Al-Khalisy 2026); the data do not show it. The port authority attributes the fall to RED III (Port of Rotterdam Authority 2026)

Linkage: the transfer and the contractible premium

Operator price on route fuel (share λ of the road increment passed on):

$$P_S^{\text{OP}} = c_s - p^M m(\sigma - g_s) - \lambda (p^R - p^M) m(\sigma - g_s)$$

Road increment: $T = (p^R - p^M) m(\sigma - g_s) V^R > 0$, route volume V^R at most the cap. Operators receive λT , sellers with access keep $(1 - \lambda)T$; the marginal buyer still pays $c_f + \bar{\tau}$, so wedge and retention are unchanged

- **Tighter road market:** the road price at the cap, p^R , is above p^M ; the gap is not estimated, and the results hold for any positive gap
- **Not counted by lenders:** the road increment is a design choice revisable at reviews, not a maritime obligation; indexing the offtake to the road credit price does not help, since the state can close the route
- **Enforcement:** $q = 1 - (1 - q_s) s$, with q_s the probability a member state enforces the sub-target and s the share of an RFNBO's premium that only the sub-target pays
- The paper gives the direction of the transfer, not its size: no price for the maritime-to-road sale is published

Welfare: transfer neutrality and three real losses

$$\text{DWL} = \underbrace{(1 - \mathcal{R}(\bar{\tau}))Qb + Q \int_0^{\bar{\tau}} \delta dG(\delta)}_{\text{leakage}} + \underbrace{\Lambda}_{\text{underinvestment}} + \underbrace{\Xi}_{\text{arbitrage}}, \quad b \equiv \psi(g_f - \sigma) - \bar{\tau}$$

- The road-to-maritime **transfer** T cancels in social welfare: redistribution, no efficiency verdict. ψ is the social value of abating one gram
- $\Lambda \geq 0$: surplus lost by delaying projects that remain worth building at utilisation $\mathcal{R}(\bar{\tau})$;
 $\Xi \geq 0$: loss from a choice of fuel that departs from the socially best one
- A road link adds a static gain $\Gamma \geq 0$ outside the maritime market; when $\lambda > 0$ and the route is not committed it also raises Λ , so its net effect **has no sure sign**, as with broader trading across performance-standard sectors (Long et al. 2025)
- Λ rests on the premise that delayed capacity is not replaced by other plants in the meantime

The option to wait: hurdle multiple and the range of unbuilt plants

- A plant is irreversible and its value uncertain: by the standard threshold rule (Dixit and Pindyck 1994; McDonald and Siegel 1986) the producer invests the first time project value reaches $V^* = w(\zeta) I$, with $w = \zeta / (\zeta - 1) \geq 1$, rising with the volatility of project value
- With no drift, w depends on volatility and the discount rate only through $u = \zeta^2 / (2r)$:

$$\zeta = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{u}}, \quad w(u) = \frac{\zeta}{\zeta - 1}$$

- **Underinvestment:** take a frictionless benchmark with $q = 1$, $\beta = 0$, $\mathcal{R}(\bar{\tau}) = 1$ and hurdle multiple w_0 . Under the status quo the haircut index is $a = q(1 - \beta)\mathcal{R}(\bar{\tau})/w(\zeta)$, and $a w_0 < 1$. For $I/y \in (a\rho^*, \rho^*/w_0]$ the benchmark builds at once and the status quo does not: investment is delayed until project value rises to the status-quo hurdle, and forgone if it never does
- R2 lowers the volatility, and so w , by guaranteeing compliance values from the investment decision through a plant's lead time

Dated hurdles: a deadline and the end of the FuelEU reward factor

	Scaled horizon rT				
Scaled volatility u	0.10	0.25	0.50	1.00	No horizon
<i>A. Deadline: the opportunity expires at the horizon</i>					
0.10	1.23	1.29	1.33	1.36	1.37
0.25	1.39	1.50	1.57	1.62	1.64
0.50	1.60	1.77	1.89	1.96	2.00
1.00	1.94	2.24	2.43	2.56	2.62
2.00	2.53	3.08	3.44	3.65	3.73
<i>B. Reward expiry: the premium on fuel used after the expiry falls to 50% of its level</i>					
0.10	1.19	1.16	1.17	1.22	1.37
0.25	1.37	1.34	1.36	1.44	1.64
0.50	1.62	1.58	1.61	1.73	2.00
1.00	2.04	1.98	2.04	2.22	2.62
2.00	2.77	2.70	2.82	3.12	3.73

Notes: Paper's appendix table of dated hurdles: lowest project value, as a multiple of sunk cost, at which investing at once is optimal. Panel B: the premium on fuel used after the FuelEU reward factor ends is 50% of its level. A grid, not a calibration.

At $u = 0.25$: 1.64 with no deadline, 1.50 at horizon 0.25; the end of the reward factor lowers it more (1.34): **invest early, not wait**.

Sensitivity of the value ratio to the allowance price

EUA, EUR/t	B3o blend	Bio-LNG, by engine			E-methanol (RFNBO)	
		Diesel	Otto slow	Otto medium	With reward	No reward
60.00	10.2	9.7	9.9	10.1	20.6	8.4
82.66	7.4	7.0	7.2	7.3	14.9	6.1
84.49	7.2	6.9	7.0	7.2	14.6	6.0
87.34	7.0	6.6	6.8	6.9	14.1	5.8
90.00	6.8	6.5	6.6	6.7	13.7	5.6
100.00	6.1	5.8	5.9	6.0	12.4	5.1

Notes: Paper's sensitivity table, Panel A: value ratio Ω_i , FuelEU at its penalty. EUR 82.66, 84.49, 87.34: minimum, volume-weighted mean, maximum spot allowance price in September 2026. Methane slip: 0.2% (Diesel), 1.7% (slow-speed Otto), 3.1% (medium-speed Otto).

- Between EUR 60 and 100 per tonne the e-methanol ratio runs from 20.6 down to 12.4; it does not move with the Dutch credit price, since RED III is never the highest or lowest instrument

Accounting rules differ across the three instruments

- **FuelEU Maritime:** well-to-wake, by the RED method; methane weighted at a global warming potential (GWP) of 25, nitrous oxide at 298
- **EU ETS:** tank-to-wake under the MRV Maritime Regulation; the CO₂ of biofuels and RFNBOs that meet the RED criteria counts as zero; from 2026 it charges CH₄ and N₂O, weighted at 28 and 265
- **RED III:** well-to-wake as well, but only for fuel sold in the member state
- A December 2025 draft amendment to the RED annexes raises the RED III and FuelEU methane weight to the ETS value of 28; boundaries would still differ, as would the nitrous oxide weights unless the draft moves them too
- The boundary matters: in a fleet model under uncertainty, well-to-wake favours bio-methanol and tank-to-wake favours ammonia from natural gas (Wang and Iris 2025)
- **Small today:** at published prices the unintended difference per tonne abated is small; the rules still matter because they change on separate dates and treat methane slip differently

Chain of custody: one document, three claims

- A Proof of Sustainability (PoS) certifies that fuel meets Article 29 criteria. Before the RED III maritime mandates it moved with the fuel; now the bunker supplier must submit it to the member state authority, and the ship operator, which owes FuelEU or ETS compliance on the fuel, holds no original
- Two partial solutions (Bureau Veritas Marine & Offshore 2026): a **Proof of Compliance** (a copy that may not carry the weight of the original in a dispute with a FuelEU verifier) and the **Union Database** (extension to marine fuels planned for early 2026; no official source confirms it; in October 2026 the Dutch authority still described it as not yet operational for its intended purpose (Dutch Emissions Authority 2026))
- The database must handle three legitimate claims on one certificate (RED III, FuelEU, ETS): **concurrent recognition**. The proposals do not describe how each claim is tied to the cargo delivered; nothing yet stops a second claim under the same instrument
- Virtual liquefaction is prohibited in the Netherlands and permitted in France and Spain; as rules may change, a bio-LNG contract relying on the silence carries a risk premium

Accounting and fuel choice; fraud and the certificate price

Fuel choice (combined value $V_i = \sum_k v_i^k$; α_i abatement per MJ)

- The operator maximizes $V_i - (c_i - c_f)$; the socially best choice maximizes $\psi \alpha_i - (c_i - c_f)$
- It prefers i to j while j is socially better iff $V_i - V_j > c_i - c_j > \psi(\alpha_i - \alpha_j)$
- A common value per gram abated $\bar{P}$ makes the ranking by compliance value the ranking by abatement; the choice is socially best when $\bar{P} = \psi$
- Common accounting is sufficient, not necessary.

Harmonized accounting alone cannot correct a common value that differs from ψ

Fraud ($\Phi_i = \sum_k v_i^k$; expected cost κ)

- Fraud is incentive-compatible when $\Phi_i > \kappa$
- Removing the multiplier lowers exposure only to its price-driven floor $\Phi_i(1)$; deterrence returns iff $\Phi_i(1) \leq \kappa$
- A duplicate claim of a genuine record earns v_i^k ; a fabricated record earns the sum
- R4 removes the gain from a duplicate claim; independent verification raises κ , but how far the paper does not estimate
- The values take FuelEU at its penalty, so they overstate what a false certificate can realize where pooled surplus trades below it

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